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Immersive Virtual Reality for Health Promotion and Primary Prevention in Psychology: Scoping Review

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Abstract

Background: Virtual reality (VR) has emerged as a promising tool in health promotion and prevention psychology. Its ability to create immersive, engaging, and standardized environments offers unique opportunities for interventions and assessments. However, the scope of VR applications in this field remains unclear.

Objective: This scoping review aims to identify and map the applications of VR in health promotion and prevention psychology, focusing on its uses, outcomes, and challenges.

Methods: A systematic search was conducted across 3 electronic databases (PubMed, PsycINFO, and Scopus) for studies published between 2010 and 2024. Eligibility criteria included empirical studies using immersive VR for health promotion and prevention, while studies using nonimmersive VR, lacking health-related applications, or focusing on clinical interventions were excluded. The review followed PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews) guidelines, and 4295 records were initially identified, with 51 studies included after screening. Data were synthesized qualitatively to identify key applications, limitations, and emerging trends.

Results: VR was primarily used in three areas: (1) delivering interventions (eg, pilot testing, skills training), (2) exploring fundamental research questions, and (3) assessing outcomes such as behavioral or psychological responses. Although VR demonstrated potential for enhancing user engagement and replicating ecological scenarios, its effectiveness compared to nonimmersive methods varied. Most studies were pilot or feasibility studies with small, nonrepresentative samples, short follow-up periods, and limited methodological standardization.

Conclusions: VR offers a versatile and promising tool for health promotion and prevention but its applications are still in the early stages. The evidence is limited by methodological weaknesses and variability in outcomes. Future research should prioritize replication, longitudinal designs, and standardized methodologies to strengthen the evidence base and expand the applicability of VR interventions.

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KEYWORDS

virtual reality; health psychology; prevention psychology; health promotion

Introduction

Background

Health and prevention psychology aims to address health-related issues to either prevent individuals from starting or continuing an unhealthy behavior (ie, primary prevention), help them to detect or reduce illness in early stages (ie, secondary prevention), or support individuals in their journey against consequences of heavier injuries or diseases (ie, tertiary prevention, [1]). Although secondary and tertiary prevention are more individual-based depending on the illness or signs or symptoms individuals need to learn to cope with, primary prevention is broader and aimed at a larger audience. Therefore, primary or universal prevention is designed to prevent individuals from the general population from getting injured or sick and aims to enable people to live a sustainable and healthy lifestyle [2,3].

In this sense, health promotion campaigns have started to integrate technological innovations such as virtual reality (VR). We refer to VR as a type of human-computer interface immersing users into a computer-generated 3D virtual environment (VE) they can interact with in a naturalistic fashion, usually via an avatar (ie, representation of the user in the VE [4]). More pragmatically, we labeled as VR any type of device that has the ability to sensorily detach the user from the outside

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world (at least sight, but also sounds, smell, and touch in some cases). This includes the use of a cave automatic VE (users are surrounded by walls displaying the VE) or a head-mounted display (HMD), which blocks the user's field of view outside of the VE and from which the user cannot turn away by simply looking away (ie, computer screens or 360° videos will not be considered VR in this definition).

The main aim of VR is to recreate a realistic, ecological context and experience while keeping some degree of experimental control over it [5-7]. Systematic reviews have reported promising results from VR-based interventions in other disciplines (eg, clinical psychology [8] and social psychology [9,10]). However, to our knowledge, there has been no review of the use of VR technologies for primary health promotion and prevention. Therefore, instead of focusing on specific research questions related to a topic, outcome, or population, the goal of this review was to map the current state of the art of the use of VR in such areas and identify gaps and future directions.

Rationale

Virtual Reality: Operating Principles

The VR literature highlights 2 essential concepts, immersion and presence, both of which are critical to the user's experience in VEs [7,11]. Immersion refers to the technological ability of a VR system to fully engage the user by replacing real-world sensory inputs with virtual stimuli. The more immersive the device, the less interface there is between the user and the virtual world. High immersion includes naturalistic interactions, such as the use of body suits to track movement, which increases the sense of realism [7]. Immersive systems create a sense that the virtual world is an actual experience rather than a mediated one. However, presence depends on the user's psychological response to the VE. It is the subjective feeling of "being there" in the virtual world, interacting with it as if it were real [12]. This sense of presence increases engagement and leads to more vivid, memorable experiences [13]. Notably, presence can be felt in both immersive and nonimmersive media, such as movies or books, as it is influenced by individual factors and not just the technological features of the medium [14].

Although immersion and presence are often related, they are not the same. Higher levels of immersion tend to enhance feelings of presence, but immersion is not a necessary condition for presence [15]. Thus, immersion can be viewed as a moderator that enhances presence but does not guarantee it [16].

Why Use VR in Health Promotion and Prevention Psychology?

VR technology has emerged as a promising tool in health promotion and prevention psychology, allowing for immersive experiences that can enhance user engagement and motivation [17,18]. VR enables researchers to create safe, ecological, and standardized VEs, where health promotion interventions can be effectively delivered and evaluated. VR presents key advantages as a tool for research and intervention in health promotion and primary prevention [7].

First, VR can be combined with devices aimed at mimicking more natural movements (eg, the use of handheld controllers or haptic devices instead of a mouse and keyboard) and can encompass the integration of full-body motor and haptic feedback when using a bodysuit. This freedom and wholeness of movement can help enhance learning through direct practice, visualization, and ultimately embodied cognition (ie, cognition linked to the body [7,19]). Hence, VR can be a relevant tool to create interventions aimed at learning health-related behaviors that require practicing skills (eg, detecting testicular disorders [20]).

Second, due to its ability to elicit embodiment, VR is well suited to elicit and enhance perspective-taking and empathy [7,21]. For example, embodying an obese avatar could enhance taking the perspective of being overweight, leading to a more effective learning of the consequences of obesity and, in turn, a greater intention to take care of individual health (ie, reduce the attitude-intention-behavior gap). Through the feeling of presence, individuals can visualize themselves in a specific situation, hence allowing a deeper sense of self-reflection [20], potentially leading to more persistent changes in behavior. VR can recreate ecological situations and environments in which users can embody an avatar and act in the virtual world as if it were real, through the feeling of presence [12].

Objective

Our goal was to identify and map how VR has been used in the field of health promotion and primary prevention. In this scoping review, we addressed three broad research questions:

1. What are the uses of VR technology in primary prevention and health promotion (ie, an overview of the goals and research questions addressed through the use of VR)?
2. What do we know so far about the effects of using VR in these fields (ie, a summary of the results)?
3. What are the challenges and limitations, if any, encountered so far?

Based on the findings of the scoping review, we drafted a list of recommendations and perspectives for the use of VR in health promotion and primary prevention.

Methods

Protocol and Registration

The scoping review protocol was drafted according to the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews) checklist [22,23]. We also conducted a synthesis without meta-analysis [24] (Checklist 1).

Eligibility Criteria

We included any peer-reviewed and published empirical article, written in English, that described a study conducted on human subjects deploying any kind of immersive VR device (eg, HMD, cave automatic VE), including 360° videos when used in a VR setup, focusing on any research question in the field of health promotion or primary prevention, from January 1, 2010, to September 16, 2024. We chose to limit the search to the last 14 years in order to generate a recent state-of-the-art overview of the field. We excluded studies conducted on nonhumans or focused on secondary or tertiary prevention interventions, such

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as psychotherapeutic treatments (eg, VR exposure therapy) and medical interventions (eg, rehabilitation), or specialized educational programs unrelated to prevention (eg, skills improvement for health practitioners). Pilot studies were not excluded from this review because of their critical role in assessing the feasibility and acceptability of interventions that may inform future primary, secondary, or tertiary prevention efforts. We excluded studies using the term "virtual reality" that described computer-based VEs involving a virtual world (eg, Second Life) or computer-related or motion-sensing devices (eg, Kinect, joystick) when they were associated with a nonimmersive VR setup (eg, non-VR video or serious game). We also used the population-concept-context framework to define our inclusion criteria. The population includes adolescents, young adults, and specific populations at risk for health issues (eg, individuals with anxiety or those at risk for substance use). The concept focuses on the application of VR technology to promote health behaviors, enhance knowledge, and improve emotional well-being. The context refers to contextual factors including the environments where VR interventions are delivered, such as schools, community centers, or health care facilities.

Information Sources and Search Process

We searched 3 databases from January 1, 2010, until September 16, 2024 (PubMed and PsycINFO). For each database, we combined 2 sets of keywords; the first set focused on health promotion and prevention psychology. For PubMed, the search strings were ("health prevention" OR "health promotion" OR "health risk communication" OR "health communication" OR "preventive psychology" OR "behavior change" OR "attitude change") AND ("virtual reality" OR "immersive virtual reality" OR "immersive virtual environment"). For PsycINFO, the search strings were ("health prevention" OR "health promotion" OR "health risk communication" OR "health communication" OR "preventive psychology" OR "behavior change" OR "attitude change") AND ("virtual reality" OR "immersive virtual reality" OR "immersive virtual environment").

Selection of Sources of Evidence

Studies that did not employ VR technology, were not peer-reviewed, were reviews or meta-analyses, or lacked empirical data were excluded from the review. The screening process was conducted in 2 stages to enhance the rigor of the selection. In the first stage, titles and abstracts of the identified studies were reviewed to determine their relevance based on the inclusion criteria. This initial screening allowed the authors to eliminate studies that were clearly outside the scope of the review. In the second stage, full-text articles of the remaining studies were assessed to confirm their eligibility for inclusion. The extraction process was conducted independently by multiple reviewers to enhance reliability and minimize bias. Any discrepancies in data extraction were resolved through discussion and consensus among the reviewers. This meticulous approach to data extraction allowed the authors to synthesize findings across studies effectively and draw meaningful conclusions regarding the efficacy and feasibility of VR interventions in health promotion and primary prevention.

Data Charting Process

The data charting process involved collecting information on study characteristics, intervention details, measured outcomes, user experience, type of materials, and sample characteristics (see Multimedia Appendix 1). Of note, approximately 63% of the studies included in the review were categorized as pilot or feasibility studies. We also recorded the type of VR technology used (eg, immersive headsets, desktop VR), the duration of the intervention, and the focus of the VR content (eg, health education, behavior change). On average, participants spent approximately 12.8 (SD 11.1) minutes using VR. We focused on health-related outcomes such as knowledge acquisition, behavioral intentions, and psychological well-being. User experience was assessed through qualitative data that provided insights into participants' enjoyment, ease of use, and perceived effectiveness of the VR interventions. Many studies found that participants found the VR experience both enjoyable and engaging, which in turn led to higher participation rates compared to non-VR interventions.

Data Items

Primary variables included study characteristics such as authorship, year of publication, study design, and sample size, which provided context for the research findings. Participant demographics, including age, gender, and health status, were also collected to understand the populations included in the studies. Intervention details were documented, focusing on the type of VR technology used, the duration of the intervention, and the specific health issues addressed. Measured outcomes were categorized into primary outcomes, such as knowledge acquisition and behavioral intentions, and secondary outcomes, including user engagement and satisfaction. User experience data were collected to assess participants' enjoyment, ease of use, and any challenges encountered during the VR interventions. In addition, limitations of the studies were noted, including issues such as small sample sizes and methodological limitations, which are critical for contextualizing the findings. It is important to note that while immersion and presence are key concepts in understanding the effectiveness of VR, these variables were not measured consistently across studies, which may affect the interpretation of results. The data elements collected were intended to provide a structured review of the existing literature, as well as identify trends, gaps, and implications for future research in the field of VR-based health interventions.

Critical Appraisal of Individual Sources of Evidence

We found that approximately 37% of the included studies were pilot or feasibility studies. These studies primarily focused on evaluating the usability and acceptability of VR interventions, which are critical for assessing the feasibility of larger-scale research. Although pilot studies provide valuable insights into user experiences and preliminary results, their small sample sizes and limited generalizability limit the ability to draw firm conclusions about the effectiveness of VR-based interventions. Mixed results have been found when comparing VR interventions to traditional methods, suggesting that VR does not always offer a clear advantage in achieving health outcomes. Key variables such as immersion and presence, which are critical

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to understanding how VR might influence health behaviors, have not been systematically evaluated. We found a lack of focus on larger, more diverse samples and aim to replicate existing studies to strengthen the evidence supporting the use of VR in health promotion efforts.

Study Selection Procedure

All search results were stored in Zotero, an open-source reference manager, and duplicates were removed. Titles and abstracts were screened first, removing articles that clearly did not match eligibility criteria. Second, full texts of the remaining articles were downloaded to define final eligibility for inclusion. For each step, 2 reviewers conducted the screening independently and compared and discussed these discrepancies until a full consensus was reached.

Data Extraction Process and Synthesis of Results

Data extraction was done by 1 reviewer, who extracted the following items from the included articles: (1) title and authors, (2) goal(s) of the study, (3) design of the study, (4) study sample characteristics, (5) VR device used, (6) main results, and (7) limitations reported by the authors. A second reviewer verified that all data were correctly extracted. Following the data extraction, we conducted a narrative analysis and synthesis of the results. Results and implications of the data extracted from the included studies were discussed by 2 reviewers in relation to the 3 research questions of the scoping review.

Results

Study Selection and Characteristics of Included Studies

The initial search identified 4295 unique articles, which were reduced to 51 eligible articles (see the PRISMA flowchart in Figure 1). Included studies were conducted in Asia (11 studies, 22%), Europe (18 studies, 35%), the Middle East (1 study, 2%), and North America (21 studies, 41%). The total sample size across all studies was 4647 participants, with an average of 91.1 participants per study. Study samples included slightly more women, with 2651 women (53%) and 1958 men (42.7%). The mean age of participants across the studies was 31.6 (SD 5.45) years. Studies primarily included adults, with 29 studies (57%) focused on adults, followed by 14 studies (28%) focused on adolescents, 7 studies (14%) focused on senior adults, and 1 study (2%) focused on children. Specific populations studied included students (7 studies, 29%), people with cognitive impairment (3 studies, 12%), and people with obesity (3 studies, 12%). Other populations studied included former smokers (1 study, 4%), NHS staff (1 study, 4%), parents (2 studies, 8%), smokers (2 studies, 8%), adults who had been in lockdown (1 study, 4%), and unvaccinated adults (1 study, 4%, see Figure 2 for details).

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Figure 1. Flowchart of the study selection process following PRISMA guidelines. A total of 4295 articles were initially identified across 3 databases. After removing duplicates and applying eligibility criteria, 51 studies were included. iVR: immersive virtual reality; PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analyses.

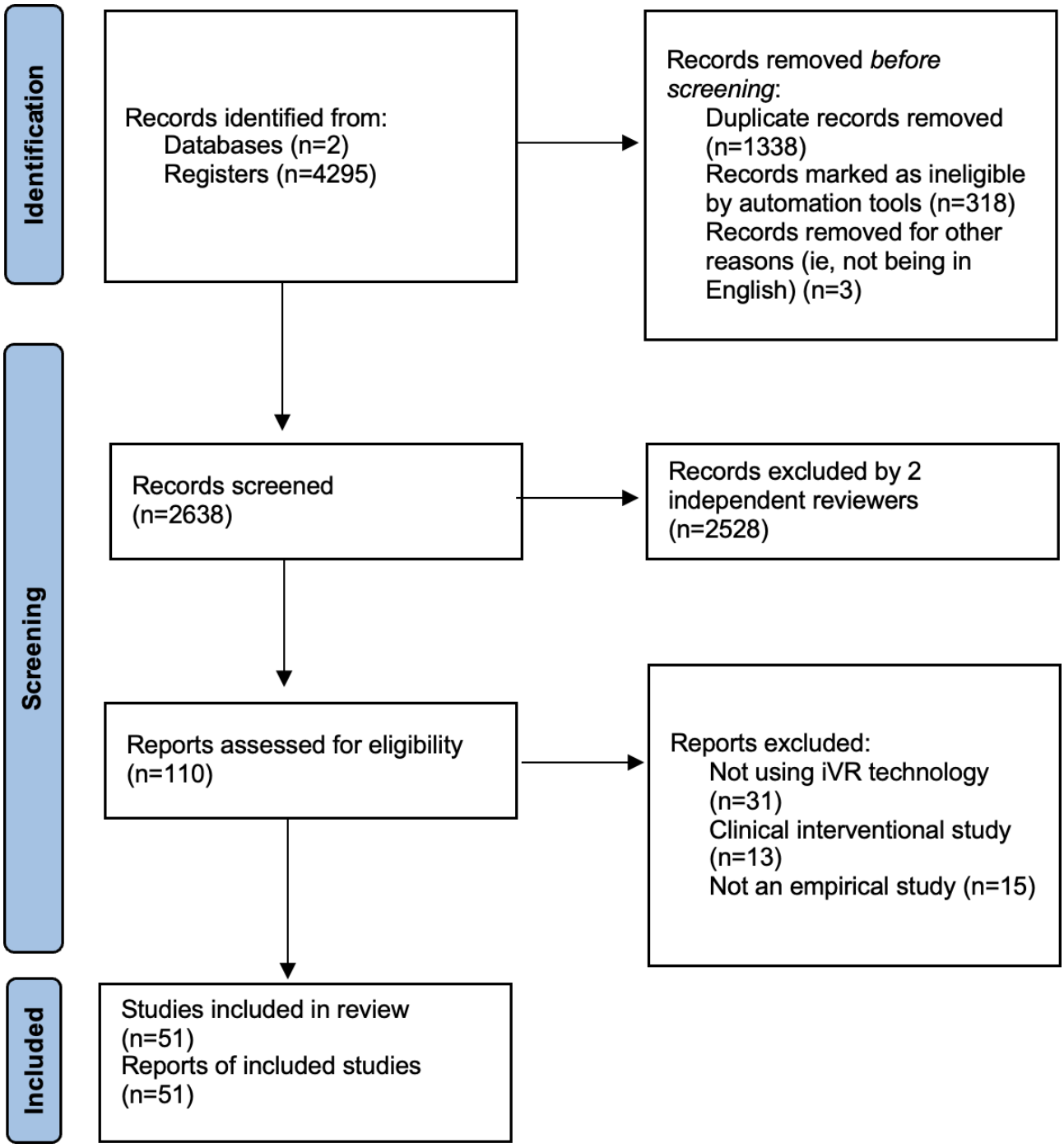

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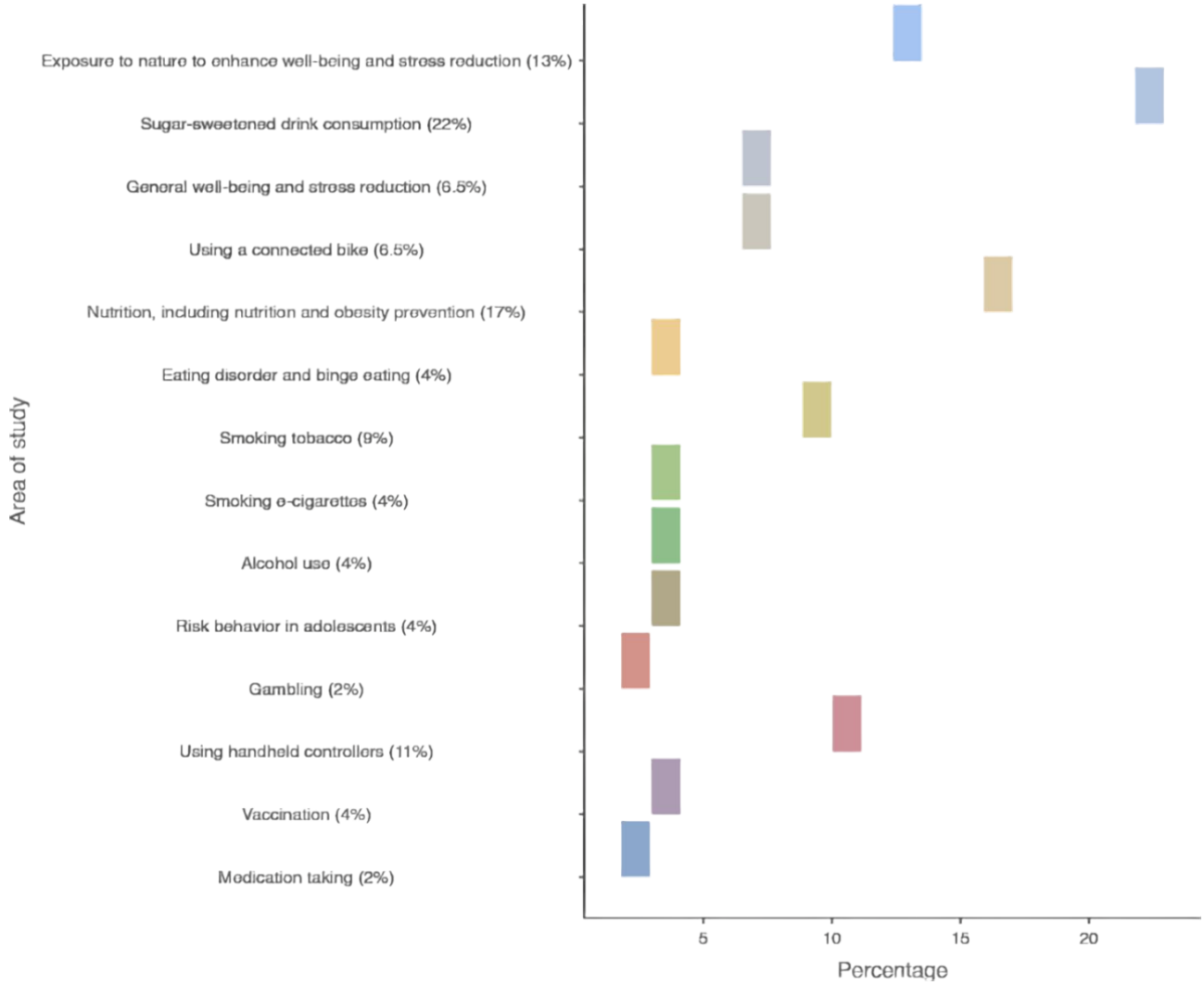
Figure 2. Overview of key outcomes from the intervention studies.



Characteristics of Sources of Evidence

The 51 included studies focused on various health-related topics (Table 1), the most predominant ones being nutrition (17%) and risky behaviors (4%). All studies used HMD, except for Lemieux et al [25], where the device used was not mentioned. HMDs were mainly Oculus (Quest, Go, or Rift, 24%), HTC Vive (17%), or Samsung Gear VR (15%). Almost half of the studies (43%) were coupled with 1 or 2 handheld controllers. Most studies (56%) included an active interaction with the VE by using 1 or 2 handheld controllers or the bodysuit to interact with the VE. About 49% of VR exposure lasted a maximum of 10 minutes, including 22% of studies with under 5 minutes of VR exposure. We estimated an average time of 12.8 (SD 11.1) minutes spent using VR, according to the information given in the articles.

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Table . Characteristics of sources of evidence.

Area of study	Studies
Nutrition, including nutrition and obesity prevention (17%)	Blom et al [26]; Isgin-Atici et al [27]; Ledoux et al [28]; Marcum et al [29]; McBride et al [30]; Persky et al [31,32]; Verhulst et al [33]
Eating disorder and binge eating (5%)	Ferrer-Garcia et al [34]; Lemieux et al [25]
Sugar-sweetened drink consumption (10%)	Blom et al [26]; Ledoux et al [28]; Marcum et al [29]; McBride et al [30]
Smoking tobacco (8%)	Borrelli et al [35]; Ferrer-García et al [36]; García-Rodríguez et al [37]; Bonneterre et al [17]
Smoking e-cigarettes (5%)	Weser et al [38,39]
Alcohol use (5%)	Guldager et al [40]; Ma [41]
Risk behavior in adolescents (4%)	Hadley et al [42,43]
Gambling (2%)	Detez et al [44]
Exposure to nature to enhance well-being/stress reduction (14%)	Alyan et al [45]; Beverly et al [46]; Brimelow et al [47,48]; Browning et al [49]; Calogiuri et al [50]
General well-being/stress reduction (10%)	Afifi et al [51]; Adhyaru et al [52]; Kim et al [53]; Riva et al [54]; Ko et al [55]; Kiper et al [56]
Using handheld controllers (7%)	Eisapour et al [57]; Fang and Huang [58]; Farič et al [59]
Using a connected bike (7%)	Bird et al [60]; Zeng et al [61,62]
Vaccination (4%)	Mottelson et al [63]; Nowak et al [64]
Medication-taking (2%)	Niki et al [65]

Results of Individual Sources of Evidence: Detailed Results

Main Identified Research Goals

We identified three main goals for using VR: (1) as a tool to deliver an intervention, with 35 articles focusing on either (1a) pilot testing or testing the feasibility of using VR materials or procedures or (1b) using VR to deliver an actual intervention (eg, skills learning, comparing VR vs other intervention modalities) to test its relative efficacy; (2) as a tool to address fundamental research questions, with 6 studies aimed at recreating ecological settings to address physiological and psychological changes when exposed to certain situations (eg, cravings elicitation); or (3) as an assessment tool, with 5 studies investigating food choices with a food buffet created in VR.

Pilot Studies: Ensuring Usability and Enjoyability

Many studies included in the scoping review were pilot or feasibility studies (about 37%, Table 2) from which we distinguished two main purposes: (1) testing VR usability for future research and seeing how target outcomes are impacted and (2) assessing users' experience with VR. First, researchers found that the use of VR in their methods was rather relevant and reached multiple target outcomes such as reducing stress using a short exposure to nature in VR [45-48,51,52,55], even though exposure durations were relatively short (3-10 minutes). The use of VR was also useful to enhance participants' physical and cognitive activity [66,67]. Finally, some studies were focused on prevention and the major advantage of VR use is its ability to involve participants directly in the preventive message, for example through gaming [68] or skill practice (eg, refusing peer pressure to vape [38]). This resulted in improved knowledge on health topics (eg, on smoking in [69]) and intentions to check for diseases (eg, [20]). It also helped to deliver information in a more traditional preventive way (eg, exposure to a preventive video in an HMD in [35] or a FestLab in [40]). Overall, pilot and feasibility studies, even if conducted on small samples, found VR to be enjoyed and accepted by participants, as well as useful and feasible, and found that it impacted target outcomes (eg, enhanced well-being, increased knowledge). These results occurred whether participants only had a one-time exposure (eg, [53,69]) or sessions over a few weeks (eg, [48]) and were found to be sustained at follow-up when measured (eg, participants reduced their tobacco intake over the month following their participation [35]).

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Table . Summary of articles and their classification within the scoping review.

Category and study	Descriptives	iVR[a] details	Objective(s)	Study design	Main conclusions
1a: Pilot or feasibility studies					
Adhyaru and Kemp [52]	n=39; mean age 36.6 (SD 10.3) years; 82% women; health care workers	HMD[b] (Oculus Go); 10 minutes	Explore if exposure to nature in iVR can help health care workers de-stress at work.	Before-after exposure; within-subject	iVR reduced anxiety, anger, and heart rate, and enhanced happiness and relaxation.
Afifi et al [51]	n=50 older adults with cognitive impairments and their family members	Immersive VR[c] system	Assess whether iVR improves quality of life and social interaction for older adults and their family members.	Feasibility study with pre-post assessments	VR improved social interaction and quality of life for both older adults and their families.
Alyan et al [45]	n=20; mean age 21.8 (SD 2.2) years; 50% women; students	HMD (HTC Vive); 5 minutes	Use iVR to reduce stress via a virtual walk in nature.	2 (environment: realistic vs dreamlike); between-subject	iVR reduced stress and enhanced mental well-being.
Beverly et al [46]	n=102; 72% women; health care workers	HMD (Oculus Go/Pico G2); 3 minutes	Explore if cinematic iVR can reduce stress in health care workers.	Before-after exposure; within-subject	iVR reduced stress, independently of previous iVR use or job type.
Bonneterre et al [17]	n=121; mean age 19.6 years; 82.5% female; university students	Sensiks Immersive VR system	Evaluate the impact of VR on memorization, attitudes, and craving responses to anti-tobacco posters.	Randomized controlled trial	VR enhanced memorization of prevention messages.
Borelli et al [35]	n=23; mean age 49.8 (SD 13.3) years; 22% women; adult smokers	HMD (Knoxlabs V2 cardboard); 5 minutes	Examine the feasibility and impact of a smoking cessation intervention during dental cleaning.	2 (video type: smoker ready/not ready to quit) × 3 (time: pre/post/follow-up); within-subject	Feasible and accepted by both smokers and dental care providers.
1b: Interventions					
Ahn [5]	n=73; mean age 20.8 (SD 1.1) years; 82% women; students	HMD (NM); 2 minutes	Test efficacy of preventive messages on sugar and sweetened beverage consumption via avatar embodiment.	2 (pamphlet only vs pamphlet plus iVR) × 2 (tailoring: others vs self) × 3 (time: pre/post/follow-up); between-subject	iVR heightened intentions to limit sugar and sweetened beverage consumption; effects were present at follow-up.
Blom et al [26]	n=99; mean age 30.7 (SD 10.9) years; 60% women; general population	HMD (HTC Vive); ≥3 minutes	Study purchase behaviors in an iVR supermarket.	2 (nudge vs control) × 2 (time pressure: 3 minutes vs no pressure); between-subject	iVR revealed changes in healthy food purchases based on nudge type.
2: Fundamental research					
Chittaro et al [70]	n=105; mean age 21.49 (SD 2.43) years; 90.5% women; students	HMD (Sony HMZ-T1); 5 minutes	Investigate links between iVR and persuasion theory, including inducing mortality salience.	2 (environment: iVR park vs cemetery); between-subject	iVR elicited mortality salience, impacted attitudes, and induced greater physiological reactions than traditional mortality salience manipulations.
Ferrer-Garcia et al [36]	n=25; mean age 29.7 (SD 13.4) years; 32% women; smokers	HMD (5DT HMD 800); time not mentioned	Assess iVR's ability to produce cravings toward tobacco smoking.	Before-during exposure to smoking cues	iVR created cravings, correlated with presence.
3: Assessment tool					
Isgin-Atici et al [27]	n=73; mean age 22.2 (SD 4.1) years; 56% women; students	HMD (HTC Vive); 5 - 25 minutes	Evaluate ease of use and efficiency of a virtual cafeteria.	2 (groups: iVR novices vs experienced); between-subject	iVR was user-friendly and effective regardless of prior VR experience.

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Category and study	Descriptives	iVR[a] details	Objective(s)	Study design	Main conclusions
Marcum et al [29]	n=221; mean age 38 (SD 5.6) years; 100% women; mothers with obesity	HMD; time not mentioned	Examine microbehaviors influencing food selection in an iVR buffet.	3 (conditions: food safety control vs behavioral risk information vs family-based risk information); between-subject	iVR enabled dynamic assessment of food choice behaviors.

[a]iVR: immersive virtual reality.

[b]HMD: head-mounted display.

[c]VR: virtual reality.

Second, most participants found VR enjoyable and fun [59,68] and quite easy to use [52]; some were asked to complete a short tutorial [27]. Even older adults were able to manipulate handheld controllers [57], but 1 study reported that the HMD is sometimes heavy for their neck to lift (1 participant dropped out because of this reason [52]). It is worth noting that some of these studies [20,59] involved the targeted population in co-designing the intervention in previous pilot studies, hence not only explicitly ensuring usability [57] but also enhancing users' satisfaction with the intervention. Co-designing an intervention with the targeted population and conducting a first pilot study on a small sample (eg, 12/33) can improve the level of satisfaction and usability of the intervention prototype, albeit ultimate user satisfaction can only be assessed following full-scale deployment of the intervention.

Relative Efficacy of VR Interventions

Interventions (39% [20/51] of the studies included in the review) using VR focused on several targets such as enhancing well-being by simulating a walk in nature (while remaining seated [49,54] or walking on a treadmill [50]) or skill learning and practice on various health topics [40,42]. Some studies were interested in delivering preventive content [40,41,71], other studies used VR's ability to create standardized conditions to test theoretical frameworks (eg, nudge and time pressure on healthy food choice [26,40]), while still others used VR to embody a specific character in order to impact health outcomes [5,33,56].

The key element of most studies included in this group is that they often compared the use of VR with other modalities to deliver an intervention; for example, delivering preventive information in VR versus a 2D screen (eg, [41,54]) or without the use of specific technology (eg, live role-playing with an instructor [64], reading a pamphlet, [61]). Some studies also compared different depths of immersion [50,60,62].

When comparing the relative efficacy of VR with other modalities, mixed results were found. For example, even though participants exercising using VR experienced an attentional shift from exercising, meaning that individuals were usually distracted and entertained by the VR setting, leading them to actually enjoy physical exercise, it was not always sufficient to obtain greater physical involvement when compared to nonimmersive physical activities [25,58,60,62]. However, some studies found no difference in outcomes between the use of VR and 2D screens [54,71], and other studies even found that a virtual walk remained less efficient than a real walk in nature for mood enhancement [49]. Some studies, using VR only, also found no impact of VR prevention interventions on target outcomes (eg, no change in physical self-perception when using VR to prevent eating disorders [39], no increased knowledge on alcohol [40]). Still, we note that VR was a great tool to induce changes in knowledge and intentions to adopt a behavior (eg, vaccination intention [61], smoking e-cigarettes [44]) and for skill practice [42].

A few recent studies [44,54] investigated the use of VR outside of the laboratory, recruiting participants who own VR devices at home. Portable VR devices have become more affordable, resulting in individuals being able to use them potentially anywhere and be autonomously engaged with VR-based interventions. Furthermore, both studies resulted in an improvement in the target outcomes (reduction of psychological distress [54], increase in vaccination [44]).

Overall, VR is impactful; it can create precise and standardized experimental situations (eg, embodying an obese or weight-gaining avatar [5,33]), and it is especially practical for skill practice and sometimes for physical activity. VR-based interventions have shown a higher degree of attendance in intervention sessions (ie, adherence) than the same intervention done without the use of VR [64]. However, when VR is only used to deliver information without leveraging its specific characteristics, such as immersivity and active use of the device (ie, interacting with the VE via a game [61]), it has often been found to have similar efficacy as more traditional ways to deliver information (eg, 2D screens).

VR to Address Fundamental Health Research Questions: A Tool to Recreate Ecological Settings in the Lab

VR can recreate real-life situations in laboratories and has been used across different domains, such as gambling [36], tobacco cravings [28,37], and food cravings [34,70], as well as for mimicking specific situations inducing certain psychological states, such as mortality salience (eg, [29]). In all studies, exposure to specific cues (eg, food items, cemetery, individuals smoking) or situations (eg, being in a pub, gambling on a slot machine) elicited both physiological (eg, increased heart rate, arousal) and psychological (eg, self-reported craving) changes, whether individuals were actively (ie, interacting with the VE) or passively (ie, watching visual content) using the VR device, suggesting that the highly immersive characteristics of VR are effective at eliciting an emotional response.

However, only 1 study compared eliciting cravings using VR versus other types of devices [34], indicating VR is not better suited to trigger a craving response than 2D pictures. It might

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be possible that this null effect was due to the passive use of VR in this specific study, as interacting with a cue in VR has been found to enhance cravings [28].

VR as an Assessment Tool in Health-Related Interventions

A total of 5 studies used VR as an assessment tool in the field of nutrition by recreating a virtual buffet displaying food [27,30-32,65], where participants' task was to collect a plate of food. Participants found the VR food buffet easy to use, independently of whether they already used a VR device in the past [27]. In this context, VR allows researchers to study precisely how many items and types of food were selected and in which quantity, enabling them to calculate the total calories contained in each plate more easily. It also helped to display to participants a standardized food buffet with diverse food items without constraints from a real food buffet (eg, expiration dates, flexibility in food types, reduced costs).

Study Limitations

The Necessity to Adapt the Use of VR to Experimental Needs

The use of VR, whether for applied or fundamental research, has shown some limitations, mainly related to the study methodology and VR technology itself (eg, cybersickness, notably in [50]). First, a majority of included studies suffered from either small sample sizes (eg, 10 participants in [65], 6 in [57]) or nonrepresentative samples (eg, students in [29], healthy and active young individuals in [58]), limiting the validity and generalizability of results. Second, the quality of the experimental designs was sometimes limited (eg, semiexperimental design with pre-post comparisons) because of a lack of a proper control condition or not conducting a rigorous randomized controlled trial [20,46]. Short-term follow-up or the lack of a follow-up altogether was also mentioned as a limiting factor in numerous studies [41,42].

Lack of Systematic Assessment of VR's Main Characteristics: Presence, Immersion, and Cybersickness

VR's effects, especially persuasive effects, seem to come from its ability to enhance presence, which is the feeling of being there during a VR experience. Hence, participants act similarly to real life in the VE because they are fully immersed in their interaction with it. The level of presence experienced by users can impact targeted variables in the intervention; participants who felt more present in the VE showed stronger positive effects on persuasion-related outcomes (eg, attitudes toward vaccination and intention to get vaccinated [61]; higher presence resulted in more reported cravings for tobacco in [37]). However, presence is rarely measured as a moderator or covariate across studies despite its potential impact on outcomes. The same applies to immersion, which was not measured across studies, despite studies often comparing different intervention modalities of varying degrees of immersion (eg, VR versus 2D screen). VR is not the only technology able to generate presence; narrative, videos, or nonimmersive VR can too [14]. Not measuring immersion or presence across different modalities limits the understanding of VR's role in driving effects on the target outcomes.

Finally, cybersickness was rarely measured across studies despite its potential negative effect on user experience and, in turn, target outcomes. Some studies, notably the ones focusing on physical activity, measured cybersickness and found that it can completely erase the positive effects of using VR (eg, walking on a treadmill while wearing a VR device led to cybersickness, which diminished the positive effects of being exposed to nature compared to the other condition, [50]). Participants who felt symptoms of cybersickness believed that it impacted their experience [59], sometimes to the point they had to drop out of the experiment [62].

Discussion

Principal Findings

This scoping review identified 51 studies published over the past 14 years that explored the use of VR in health promotion and prevention psychology. Our findings revealed three primary applications of VR: (1) as a tool to deliver interventions, either in feasibility testing or actual implementation; (2) as a means to address fundamental research questions; and (3) as an assessment tool for health-related outcomes. Although VR shows significant promise in creating immersive and engaging interventions, our review highlights the variability in effectiveness and common challenges such as small sample sizes, short follow-up periods, and limited methodological standardization.

VR technology use for health promotion and prevention research is relatively recent, with studies in this review indicating its potential as a promising tool to deliver and assess interventions. For instance, VR was effective in simulating realistic scenarios to engage participants in skills-based learning and decision-making tasks, such as risk-reduction behaviors [42,61]. VR allows researchers to create safe, ecological, and standardized VEs in which it is possible to deliver and evaluate health promotion and preventive interventions [42]; recreate situations or environments that can elicit strong emotional, physiological, behavioral, or psychological responses (eg, mortality salience [29]); and assess outcomes (eg, cravings, food choices) with a multimeasure approach included in VR technologies (eg, psychological, physiological, and behavioral measures). This scoping review identified 51 studies concerning the use of VR technology in the field of health promotion and prevention psychology published within the past 14 years. We mapped (1) the goals and research questions addressed through the use of VR in this field, (2) its effects in the identified areas, and (3) its main challenges or limitations. We identified three main applications of VR in this field: (1) as a tool to deliver an intervention, either (1a) pilot or feasibility testing VR materials or procedures or (1b) using VR to deliver an actual intervention (eg, skills learning, comparing VR vs other intervention modalities) to test its relative efficacy; (2) as a tool to address fundamental research questions; and (3) as an assessment tool.

Comparison to Prior Work

Due to the relative novelty of VR in this field, only 51 eligible studies were published in the past 14 years. Research so far has mostly focused on feasibility or pilot studies, aimed at testing the ability of VR to be integrated into interventions [69], with

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a minority of studies focusing on answering fundamental research questions through the use of VR [28]. Most studies employed semiexperimental designs without a control or comparison group and often had a short or no follow-up, limiting the validity and generalizability of results. Studies also included relatively small samples and were often nonrepresentative of the general population (eg, students). However, as the use of VR in the field of health promotion and prevention is still in its infancy, it appears natural to see a stronger focus on pilot or feasibility studies in the published literature.

Strength and Limitations of the Scoping Review

When considering whether VR is effective in health prevention, it should first be noted that the effectiveness of VR interventions was variable. For instance, while some studies indicated that VR could enhance user engagement and motivation [59], others found no significant differences in outcomes compared to traditional methods [71]. This highlights the need for further research to clarify the conditions under which VR is most effective. This scoping review showed that sometimes VR use is not systematically more effective in achieving target outcomes than its nonimmersive equivalents [41,54,71]; we supposed that to be more effective, VR should be used for its specific immersive characteristics, such as gamification or embodiment, which directly involve the user. For example, skills practice in VR was more effective than role-playing in real life to learn about risk behaviors and ways to avoid them (eg, buying condoms for safer sex) due to VR scenarios' ability to recreate a situation that is realistic, induce emotional changes in the user as the scenario goes on, and finally, make the user have a real first-person experience [42]. Similar results appeared in [61], in which VR was used to represent a vaccination intervention to stop flu spread (ie, participants used handheld controllers to actively send immune cells to prevent flu transmission), whereas in other conditions, participants were just passively watching (a video on a 2D screen or a pamphlet).

It is important to consider the limitations of this review when interpreting the findings. First, as the use of VR in health promotion and prevention psychology is a relatively recent phenomenon, our literature search focused on the last 14 years (2010 - 2024). This resulted in the inclusion of 51 eligible articles, which may have excluded earlier or less accessible studies. However, the majority of included studies (63%) were published between 2020 and 2024, reflecting the increasing affordability and accessibility of VR technology for research in recent years. Therefore, the likelihood of missing pivotal studies is low. Second, the search strategy did not include gray literature, which may have reduced the total number of eligible articles and introduced publication bias by excluding studies with nonsignificant or null results (the file drawer effect). To address this gap, future reviews should consider including gray literature to provide a more comprehensive overview of the field. Third, some studies lacked sufficient reporting of critical aspects such as sample characteristics (eg, size and demographics) and details of VR implementation (eg, exposure duration, type of VR technology used). This limited our ability to draw broad conclusions about the efficacy and applicability of VR in this area. Addressing these reporting gaps in future research will improve the comparability and quality of evidence in this rapidly evolving area of study. Fourth, although our literature search was updated during the initial revision, which was completed just a few weeks prior to this submission, we recognize that VR research is advancing rapidly. It is therefore possible that new studies may emerge shortly after the conclusion of our search period, which may influence the results of future reviews. To address this, future updates could consider conducting more frequent searches or establishing a continuous review process to ensure that all emerging data are included in real time. However, we are confident that this review accurately reflects the state of the literature as of our latest search.

Perspectives and Future Research Directions

Standardization of Designs and Replication

Although the results of our scoping review suggest that VR has potential as a tool for health promotion, the field is still in its infancy. Many studies in this area are limited by small sample sizes, short follow-up periods, and inadequate experimental control. Replication is essential to strengthen the reliability and validity of these findings [72,73]. Replication of these studies in diverse populations and settings will help confirm the generalizability of the findings and identify any boundary conditions, such as differences in user demographics, technology exposure, or the specific health behaviors targeted [74,75]. In addition, replication can shed light on the mechanisms underlying the effectiveness of VR interventions, which may vary depending on the context and population studied. Therefore, further replication is essential not only to solidify current evidence, but also to ensure that VR interventions are applicable and effective across a wide range of health promotion and primary prevention efforts. Replicating existing results to increase the amount and quality of empirical evidence supporting the use and benefit of VR in this field is needed. For example, in this scoping review, we saw that individuals showed an increased knowledge regarding health-related topics [20,69] or changed their behavioral intentions [44,61] when exposed to a VR intervention. However, not all studies provided evidence to fully support these claims [47,63], in addition to the lack of any perspective on how long these effects last or if they are applicable to less specific populations. Therefore, a focus on study replication can strengthen the advancement of research in this field and at the same time prevent a replication crisis, as observed in other fields of behavioral sciences and medicine [76]. There is also a critical need for future research to employ longitudinal study designs. Long-term follow-up is particularly important in preventive psychology, where sustained behavior change and long-term health outcomes are key indicators of success.

VR vs Nonimmersive Apparatus

The effectiveness of VR compared to nonimmersive interventions, such as 2D presentations, remains controversial. Evidence from the studies included in this review showed mixed results. Although some studies reported that VR interventions increased engagement and enjoyment, others found no significant differences in outcomes compared to nonimmersive methods [59,71]. The immersive features of VR, such as gamification and embodiment, appear to be particularly effective in scenarios that require active user involvement. For example,

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participants who practiced risk-avoidance skills in VR showed better retention than those who used real-life role-playing [42]. Similarly, the use of VR in interactive scenarios, such as vaccination education, showed higher levels of engagement than passive modalities such as 2D videos or pamphlets [61]. However, studies have also shown that VR does not always outperform traditional methods in terms of physical activity or knowledge acquisition. This variability highlights the need for future research to clarify the specific contexts in which the immersive qualities of VR are most effective. Systematic assessment of key mechanisms such as presence and immersion could help determine whether VR's effectiveness is primarily due to its immersive nature or to other factors such as interactivity or novelty.

Assessing presence and immersion is crucial for understanding the mechanisms underlying VR and its effects [14]. Evaluating the feeling of presence helps determine the extent to which participants are psychologically immersed in VEs and allows for the identification and correction of potential errors in the VE that could influence presence and, consequently, the effectiveness of VR-based interventions or content. Additionally, addressing such errors can prevent cybersickness and ensure the smooth execution of experiments [50]. Measuring presence and immersion provides valuable insights into individuals' capacity to engage with VR compared to nonimmersive interventions and helps identify how these factors correlate with target outcomes.

Set Up for Success

Conducting feasibility or pilot studies to test the VR procedure and VEs is recommended. As shown in the scoping review, evaluating the enjoyability, usability, and safety of the procedure can be very helpful. Finally, co-designing the VR-based intervention with participants from the targeted population can enhance the relevance, validity, and user experience with the intervention itself. Cocreating a procedure with participants could induce a bias in their judgment, making them judge the intervention more positively than it actually is. Pilot testing with different groups of participants is recommended to validate the final design.

Make It Simple and Clear for Participants

VR studies are attractive to participants (eg, higher attendance for intervention sessions than the non-VR condition in [19,42,77]), but they can be complex to follow all the way through (ie, risk of cognitive overload, fatigue [78]). When designing studies using VR, keeping them as simple and short as possible will minimize participant burden and fatigue. It is also highly possible that most participants have never experienced VR before, so making sure they understand how to move and interact with the environment at first is necessary. If possible, we recommend doing a short tutorial on how to use the controllers or putting the participant in a tutorial VE before the experimental procedure. The participants can then fully concentrate on what is happening in the VR rather than think about how to interact with the VE.

Conclusion

This scoping review provides an overview of VR's emerging role in health promotion and prevention psychology, highlighting its potential to create immersive and engaging interventions. Although VR has shown promise in delivering health interventions and answering fundamental research questions, its effectiveness remains variable, and many studies are limited by methodological constraints. Future research should prioritize replication, longitudinal designs, and standardized methodologies to strengthen the evidence base and realize the full potential of VR in this field.

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Data Availability

This scoping review is based on a synthesis of publicly available research articles. The datasets analyzed during this study are derived from published sources that are referenced within the manuscript. No new datasets were generated.

Authors' Contributions

SB contributed to the conceptualization, formal analysis, methodology, and writing of the original draft of the manuscript. OZ was involved in the conceptualization, formal analysis, methodology, writing of the original draft, and reviewing and editing the manuscript, while also providing supervision throughout the project. MB participated in the conceptualization, methodology, and writing of the original draft, and offered supervision during the research process.

Multimedia Appendix 1
Summary of Studies Using Virtual Reality for Health-Related Behavioral Interventions.
[DOCX File, 37 KB - xr_v2i1e49923_app1.docx]

Checklist 1

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PRISMA-ScR checklist.
[PDF File, 326 KB - xr_v2i1e49923_app2.pdf]

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Abbreviations

HMD: head-mounted display
PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews
VE: virtual environment
VR: virtual reality

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Applications of Augmented Reality for Prehospital Emergency Care: Systematic Review of Randomized Controlled Trials

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Abstract

Background: Delivering high-quality prehospital emergency care remains challenging, especially in resource-limited settings where real-time clinical decision support is limited. Augmented reality (AR) has emerged as a promising health care technology, offering potential solutions to enhance decision-making, care processes, and emergency medical service (EMS) training.

Objective: This systematic review assesses the effectiveness of AR in improving clinical decision-making, care delivery, and educational outcomes for EMS providers.

Methods: We searched databases including PubMed, Cochrane CENTRAL, Web of Science, Institute of Electrical and Electronics Engineers (IEEE), Embase, PsycInfo, and Association for Computing Machinery (ACM). Studies were selected based on their focus on AR in prehospital care. A total of 14 randomized controlled trials were selected from an initial screening of 2081 manuscripts. Included studies focused on AR use by EMS personnel, examining clinical and educational impacts. Data such as study demographics, intervention type, outcomes, and methodologies were extracted using a standardized form. Primary outcomes assessed included clinical task accuracy, response times, and training efficacy. A narrative synthesis was conducted, and bias was evaluated using Cochrane's risk of bias tool. Improvements in AR-assisted interventions and their limitations were analyzed.

Results: AR significantly improved clinical decision-making accuracy and EMS training outcomes, reducing response times in simulations and real-world applications. However, small sample sizes and challenges in integrating AR into workflows limit the generalizability of the findings.

Conclusions: AR holds promise for transforming prehospital care by enhancing real-time decision-making and EMS training. Future research should address technological integration and scalability to fully realize AR's potential in EMS.

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KEYWORDS

prehospital emergency care; emergency medical services; randomized controlled trials; clinical decision support; training; augmented reality; emergency; care; systematic review; BLS; procedures; traumatic injury; survival; prehospital; emergency care; AR; decision-making; educational; education; EMS; database; technology; critical care; basic life support

Introduction

Overview

The prehospital setting represents a critical area of emergency medical care. Emergency medical services (EMSs) providers, such as emergency medical technicians, firefighters, and paramedics care for diverse patient populations in variable in highly acute settings; they are often the first to respond to life-threatening scenarios such as traumatic injury or cardiac arrest. Innovations in prehospital care have led to improvement in patient outcomes over the past several decades, including a

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reduction in early deaths following traumatic injuries and improved survival from out-of-hospital cardiac arrest following early initiation of basic life support (BLS) procedures [1-5]. However, there remain significant challenges to providing high-quality prehospital emergency care, especially in resource-limited settings. Prehospital emergency care literature reports that top research priorities include augmenting the education and training of EMS personnel as well as improving the management of patients with life-threatening conditions such as asthma exacerbation, traumatic brain injury, and cardiac ischemia [6,7]. Further, improving the availability and response quality of medical control physicians for EMS systems has been cited as an additional area of interest [8].

With the need for improvements in both real-time decision support in prehospital care and the education and training of prehospital care providers, researchers have posited the utility of integrating AR into the prehospital setting. AR technologies are tools to superimpose digitally generated 3D and 2D visual information into a user's environment in real time for display and guidance. Unlike virtual reality, in which a user is completely immersed in a virtual environment that occludes their physical environment, users of AR technologies can interact with both their physical environment and digitally generated images [9].

AR already has significant implications within health care, with AR-based clinical and training modalities beginning to emerge within several medical fields [10-13]. The most well-documented examples come from surgical specialties, which have for years used AR-based equipment as clinical decision support (CDS) and training tools to practice intricate procedures; additionally, many subdisciplines including bariatric surgery, oral-maxillofacial surgery, and neurosurgery use AR-based minimally-invasive robotic procedures [14-19]. Experts have suggested that AR-based CDS tools may prove useful to a variety of prehospital applications, such as providing real-time decision support for patient resuscitation or enhancing BLS education.

To date, there have been few systematic examinations of AR in emergency medicine (EM), with even fewer specifically investigating prehospital emergency medical care. This manuscript thus presents a systematic review of randomized control trials (RCTs) investigating applications of AR in prehospital emergency medical care. Our primary objective is to evaluate the efficacy and effectiveness of AR applications in improving patient outcomes, care processes, and learning outcomes in the prehospital emergency care setting. Our secondary objectives are to identify challenges and limitations for the implementation of AR-based CDS and training tools in prehospital EM and to explore future directions for AR applications in these domains.

Methods

Literature Search

A systematic review of the available literature was performed to investigate the effect of AR on prehospital emergency medical care. Eligibility criteria for inclusion in the systematic review included peer-reviewed manuscripts published between 1970 and 2024 (June 10) in English-language journals. A search was conducted of online academic databases including PubMed, CENTRAL, Web of Science, Institute of Electrical and Electronics Engineers (IEEE), Embase, PsycInfo, CINAHL Complete, and Association for Computing Machinery (ACM). Detailed search strategy across databases for identifying studies on AR in prehospital emergency care can be found in Multimedia Appendix 1.

Full-Text Review

A search of these 8 academic databases yielded 2081 manuscripts for review. Two independent reviewers first screened titles and abstracts to remove duplicates (n=726) as well as manuscripts that were not related to EM (n=1228). A full-text review of 127 studies was conducted by 8 independent researchers to assess their eligibility. Studies were included in full-text screening if a reviewer consensus of 2 reviewers deemed the study eligible. Each study during full-text screening was reviewed by 2 of the 8 reviewers independently and consensus was determined by a third reviewer. Data extraction was conducted independently by 2 reviewers using Covidence software (Veritas Health Innovation), which facilitated the management and review of manuscripts. Each reviewer independently extracted data, including study characteristics, participant demographics, intervention details, and outcome measures. Any discrepancies in the extracted data were resolved through discussion, with a third reviewer stepping in to make the final decision when necessary. No automation tools were used in the data extraction process. The full data extraction form can be seen in Multimedia Appendix 2.

Criteria for Inclusion

Criteria for inclusion into the final systematic review included full RCT or crossover RCT design; study setting in an EM; and use of wearable, handheld, or projection-based AR in intervention. Studies were included if they investigated the impact of AR on health care professionals or health care students, including emergency responders, paramedics, emergency medical technicians, medics, EM physicians, residents, or fellows, physician assistants, medical and health care students, surgeons, nurses, firefighters, law enforcement officers, or other relevant population (eg, lifeguards, other university students and lay first-responders, or unspecified medical specialties). Studies were also excluded if they were only a description of the technology without learning, performance, or other intervention outcomes.

Key Data Extracted

Primary outcomes of interest included patient outcomes or clinical performance outcomes such as task completion time, accuracy, number of attempts, and errors. Secondary outcomes included user experience or human factors outcomes such as technology acceptance, workload, stress, and cyber- or simulator-sickness. Key data for analysis was extracted from each of the included manuscripts by 2 independent reviewers using a standardized data extraction form. All data were collected and recorded using Microsoft Excel software. Data collected included study characteristics, participant

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demographics, AR information, outcome measures, results, and limitations.

In addition to primary outcome measures such as task completion time, procedure accuracy, and protocol compliance, we collected data on several other key variables. These included study characteristics (publication year, country of study, design type, sample size), participant characteristics (professional roles such as first responders, paramedics, medical students; study population size; and whether the setting was civilian or military). Intervention characteristics were also documented, focusing on the type of AR platform used (eg, HoloLens, Vuzix, and Google Glasses) and the intervention context (real-time clinical support or educational training). Secondary outcome measures like user experience, technology acceptance, workload, and the occurrence of simulator sickness were also analyzed. No assumptions were made about missing or unclear data, and any such data were marked as "not reported."

Consensus

Consensus between reviewers was tracked via Microsoft Excel spreadsheet and calculated using Cohen κ, with an average of 0.71 (95% CI 0.635 - 0.785). The quality and potential bias of the included studies were evaluated on a manuscript level by independent reviewers using Cochrane's risk of bias tool [20], which can be seen in Multimedia Appendix 3, and reviewed by group consensus. The literature review and evaluation process are detailed in Figure 1. All data were summarized collectively and reported as an aggregate as well as in subgroups including "education and training" and "clinical decision making". Qualitative and descriptive data were synthesized narratively. The review protocol can be accessed in the Multimedia Appendix 2.

Results

Characteristics of Included Studies

Figure 1 presents the review procedure and the resulting number of relevant papers based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [21]. The characteristics of the 14 studies included in this systematic review are summarized in Table 1.

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Figure 1. Systematic literature review procedure and the resulting number of relevant papers using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [21]. RCT: randomized controlled trial.

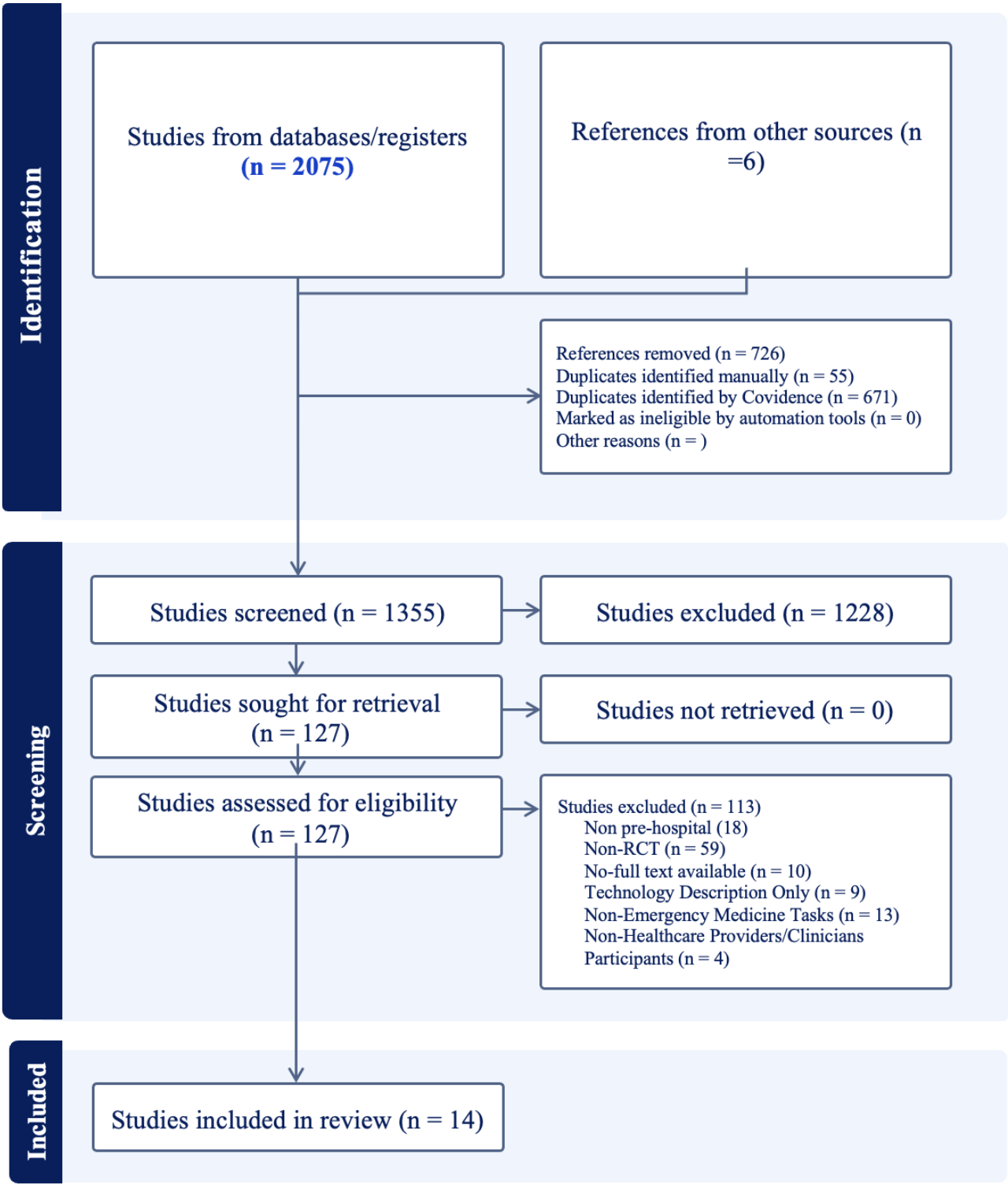

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Table . Summary of studies evaluating augmented reality (AR) interventions in prehospital care, including study populations, AR platforms used, primary outcomes, and main findings across various emergency medical scenarios.

First author, publication year	Study population and sample size	AR intervention; platform	Primary outcome measures	Main findings
Rebol et al, 2023 [22]	First responders (n=25)	Real-time assistance for CPR[a] performance; HoloLens	CPR performance metrics (compression depth and rate)	No significant performance difference between mixed reality and control group
Koutitas et al, 2019 [23]	EMS[b] cadets (n=30)	Training module for the operation of AmBus systems; HoloLens	Time to task completion and error rate	Significant reduction in task completion time and error rate in AR group
Gruenerbl et al, 2018 [24]	Nursing students (n=50)	CPR training module; Google glasses	CPR performance metrics (compression depth and rate) before and after training	Significant improvement in posttraining performance in AR group
Doswell et al, 2020 [25]	First responders (n=10)	BLS[c] procedures training module; HoloLens	Time to correct procedure performance	No significant difference in performance time between AR and control group
Collington et al, 2018 [26]	Firefighters (n=10)	BLS procedures training module; Moverio glasses	Performance in simulated trauma scenarios	Significant improvement in self-reported hands-on skills proficiency in AR group
Barcala-Furelos et al, 2023 [27]	Lifeguards (n=38)	Real-time assistance for simulated infant delivery; Vuzix	Performance time and compliance with protocol	Significantly improved protocol adherence in AR group
Follman et al, 2019 [28]	Paramedics (n=31)	Real-time assistance in MCI[d] triage; ReconJet	Screening time and assessment accuracy	Significant improvement in triage accuracy in AR group
Du et al, 2022 [29]	Medical students (n=20)	Tactical Combat Casualty Care (TCCC) training module; HTC VivePro	Posttest knowledge acquisition	No significant improvement in posttest scores between AR and control groups
Aranda-García et al, 2024 [30]	Health sciences and nursing students (n=60)	CPR and AED[e] training module; Vuzix	Time to task completion, adherence to BLS protocol, CPR performance	Significantly improved CPR quality and protocol adherence in AR group
Follman et al, 2021 [31]	Non-EM[f] health care professionals (n=40)	Real-time assistance in MCI triage; ReconJet	Time to triage; triage accuracy	Significantly decreased triage time in non-AR; no difference in accuracy
Hou et al, 2022 [32]	Health care university students (n=27)	CPR training module; HoloLens	CPR performance metrics (compression rate and depth)	No significant performance difference between AR and control groups
Apiratwarakul et al, 2022 [33]	Emergency physicians, nurses, and EMTs[g] (n=68)	Real-time assistance in MCI casualty detection; HMT-1	Time to completion; accuracy of casualty count in simulated MCI	Significantly decreased time to task completion in AR group, no significant difference in accuracy
Azimi et al, 2018 [34]	EM providers (n=20)	Training in advanced life support procedures; HoloLens	Task performance, task time	No significant difference between AR and control groups
Glick et al, 2021 [35]	Medical students (n=13)	Remote guidance in performing chest thoracotomy; HoloLens	Procedure quality rated by independent observer	Significantly improved procedure quality rating in AR group

[a]CPR: cardiopulmonary resuscitation.

[b]EMS: emergency medical service.

[c]BLS: basic life support.

[d]MCI: mass casualty incident.

[e]AED: automated external defibrillator.

[f]EM: emergency medicine.

[g]EMT: emergency medical technician.

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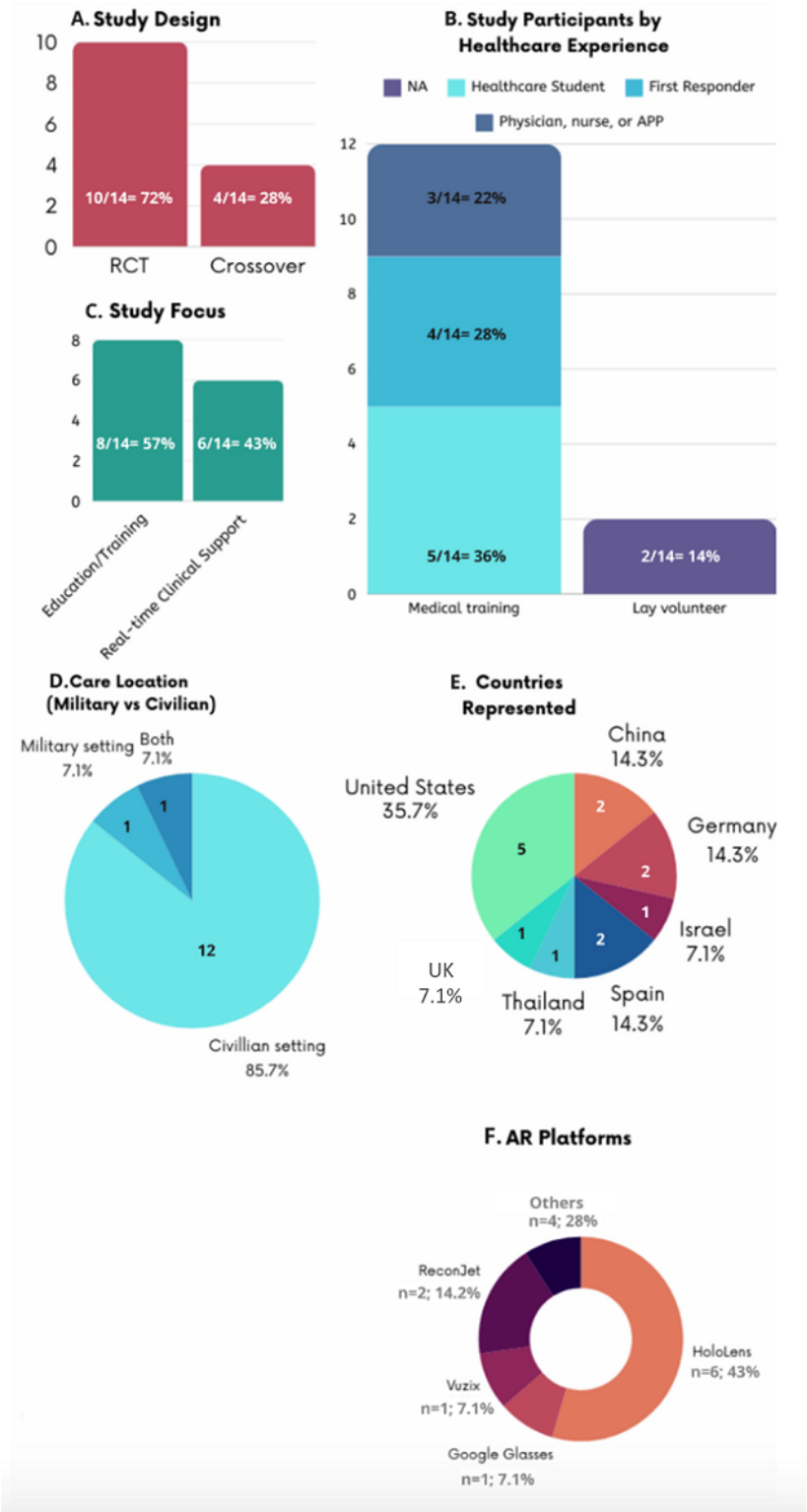
Type of Study Design

Figure 2 highlighted the summary-level study characteristics of the 14 studies. Figure 2A and C shows the distribution of studies by study design (Crossover RCT and Full RCT) and their focus areas: real-time decision support, training or education, or both. Full RCTs are the most frequent, with 4 studies focused on training or education and 3 on real-time decision support. Additionally, one study addressed both focus areas. Crossover RCTs primarily focus on training or education (4 studies), with one study focused on real-time decision support.

Figure 2. Summary characteristics of 14 included studies.



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Settings and Regions

The 14 studies included a total of 420 participants and were conducted in 7 different countries. A total of 10 (71%) studies were full RCTs while 4 (29%) studies used a crossover design. Overall, 12 (86%) studies were conducted in civilian settings while 1 (7%) study was conducted in a military setting and 1 (7%) study used both military and civilian settings (Figure 2E). Eight (57%) studies used AR for use in task training and education, while the remaining 6 (43%) used AR to provide real-time decision support for clinical scenarios. All 14 (100%) studies used medical simulation rather than real clinical encounters to test their AR interventions.

Measured Outcomes

While specific outcome measures varied, all studies aimed to compare the efficacy of their AR intervention relative to the current standard of practice. Outcomes examined included time to initiation or completion of desired procedure or intervention (n=5) percentage of correctly informed procedures, procedure quality, or error rate (n=8), and knowledge acquisition (n=1). Overall; 57% (n=8) found statistically significant improvements in their desired outcomes using AR modalities, while 36% (n=5) indicated no significant difference, and 7% (n=1) demonstrated worse performance following AR interventions.

Type of AR Platforms

All studies used wearable head-mounted displays to deliver their AR intervention (Figure 2F). The most used AR platform across studies was HoloLens goggles (6/14; 43%); other AR platforms used included Vuzix (n=1), Google glasses (n=1), ReconJet (n=2), Epson Moverio (n=1), HTC Vive Pro (n=1), and HMT-1 (n=1). A description of the AR platforms used in the 14 studies is presented in Table 2.

A variety of apps and software platforms were used across the 14 studies; selected novel interventions are highlighted in Table 3.

Table . Comparison of augmented reality/virtual reality (AR/VR) devices used in prehospital simulations, showing manufacturer, model, release date, price, and key features.

Device	Manufacturer; models and release date; and retail price	Capabilities
HoloLens	Microsoft; V2 (2019); US $3500	Eye-tracking, audio and speech command, spatial mapping, MR[a] capture, Windows connectivity
Google Glasses	Google X; Explorer (2019) NOTE: no longer manufactured; US $999-US $1848	Voice command, internet browsing, camera, calendar, android iOS
Moverio	Epson; BT 35-e (2018); US $200-US $800	Voice recognition, high definition (HD) display, drone connectivity, remote service, and support
Vuzix	Vuzix; M400 (2020); US $1799	Voice recognition, eye-tracking, spatial mapping, iOS and Android compatibility, waterproof
RealWear	RealWear; HMT-1 (2018); US $797-US $1500	Voice-activated display, noise cancellation, voice-activated, outdoor-compatible display, water and shock resistant, android and Bluetooth compatible, 20-degree field of view
ReconJet	Intel; Smart Glasses (2015); US $699	3-axis sensor, biometric tracking data (heart rate, sleep, etc), GPS, accelerometer, microphones, android iOS compatible, Bluetooth and wifi connectivity
HTC VivePro	HTC; VivePro 2.0 (2021); US $699-US $1999	5k resolution, submillimeter tracking capabilities, balanced ergonomic, 120-degree horizontal field of view

[a]MR: mixed reality.

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Table . Selected augmented reality (AR) apps and software platforms in 14 prehospital included studies.

App	Description	Platform (location)	Manuscript
PRIOR	Android app for technical support in MCI[a] triage	Tech2Go GMBH Mobile System (Hamburg, Germany)	Follman et al, 2019 [28]
AUDIME	Android app for technical support in MCI triage in the disaster setting	Tech2Go GMBH Mobile System (Hamburg, Germany)	Follman et al, 2021 [31]
AMBUS	App for learning layout of Ambulance Bus Systems	Unity Game Systems (San Francisco, CA)	Koutitas et al, 2019 [23]
Tensor Flow	Artificial intelligence android app for assistance with casualty detection	Google (Mountain View, CA)	Apiratwarakul et al, 2022 [33]
Juxtopia CAMMRAD PREPARE	App for training in BLS[b] procedures	Juxtopia AR systems (Baltimore, MD)	Collington, 2018 [26]

[a]MCI: mass casualty incident.

[b]BLS: basic life support.

Applications

AR as CDS Tools

A total of 6 studies examined AR-based real-time decision support in the prehospital setting. Rebol et al [22] investigated AR-based real-time feedback for adult cardiopulmonary resuscitation (CPR). They found no significant difference in CPR quality in non–health care university students receiving real-time mixed reality–based feedback on performance as compared with students receiving feedback via standard video conference. Barcala-Furelos et al [27] investigated an AR-based intervention aimed at guiding lifeguards assisting in imminent childbirth situations. They found significantly higher adherence to out-of-hospital birth protocols in the AR-intervention group than in the control group ($P<.05$ for all protocol variables). Follmann et al [28] found that real-time AR-based guidance in mass casualty incident (MCI) triage led to a significant improvement in triage accuracy over the control group, which performed triage without AR assistance ($P=.04$). A similar result was found by Follman et al [31], which examined the effect of AR support on MCI triage time and accuracy; they found that triage time was significantly reduced in the control group ($P<.001$) but found no difference in triage accuracy between groups. Apiratwarakul et al [33] employed an AR intervention for assistance in casualty identification; results demonstrated a decreased time to completion of casualty count in the AR group ($P<.05$) but no significant difference in accuracy. Glick et al [35] investigated real-time AR-based guidance for medical students in performing a chest thoracotomy and found that expert rating of procedure quality was significantly improved in the AR group ($P=.004$).

AR as Training Tools

A total of 7 studies examined the utility of AR for education and training in the prehospital setting. Two studies (Doswell et al [25] and Collington et al [26]) investigated AR-augmented training for BLS procedures such as Narcan administration and tourniquet application. Doswell et al [25] found no significant difference in procedure time and accuracy between the AR training group and control group; Collington et al [26] showed an increase in self-reported skills proficiency in the AR training group (mean 2.2, SD 1.03) but no significant difference in clinical proficiency. One study [34] examined the efficacy of an AR-based training module on performing advanced life support procedures, including needle chest decompression, direct intravenous placement, and cricothyroidotomy, but found no significant difference in procedure performance between the AR and standard training groups. One study [23] demonstrated that an AR-based training module for familiarization with an AmBus system led to a 10% reduction in time to task completion (involving finding objects on the AmBus) and 34% reduction in errors than the group receiving standard audiovisual-based training. Two studies (Du et al [29] and Follman et al [31]) examined AR-based training for tactical combat casualty care (TCCC) and MCI triage. Du et al [29], which examined TCCC knowledge gain based on pre and posttraining tests, found no significant performance difference between the AR-based training group and the control group.

A total of 3 studies (Gruenerbl et al [24], Aranda-García et al [30], and Hou et al [32]) specifically examined the performance of adult CPR following AR-based training modules. Two of the 3 studies (Gruenerbl et al [24]; Aranda-García et al [30]) found significant improvement in aspects of CPR performance following AR intervention. They demonstrated a significantly improved percentage of time spent performing chest compressions at the correct depth and rate among nursing students receiving AR-based instruction as compared with standard teaching ($P<.001$, $F=14.85$). Aranda-García et al [30] demonstrated significant improvement in the percentage of chest compressions performed with adequate chest recoil ($P=.008$) among health sciences and nursing students receiving AR-based instruction as compared with control; however, they did not find a significant difference in other metrics. Hou found no significant difference in CPR performance (chest compression rate and depth) receiving AR-based training as compared with instructor-led training.

Risk of Bias Analysis

Risk of bias of studies was assessed via Cochrane's risk of bias tool, which examined parameters including sampling technique, adequacy of randomization, reliability of outcome measures, and statistical power (Multimedia Appendix 3). Overall, the

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quality of the included studies was judged to be high. Each of the 14 studies was examined on a manuscript level with consensus reached between 8 independent reviewers. All 14 studies were determined to have a randomized design, with 10 comprising full RCTs and 4 having a crossover design. Most studies were found to have adequate randomization methodology, similar baseline participant characteristics, reliable outcome measures, and a participant dropout rate below 20%. Two of the 14 studies were recorded as lacking sufficient sample size to achieve 80% power with one recorded as "unable to be determined."

Discussion

Principal Findings

This systematic review sought to examine the application of AR to emergency medical care in the prehospital setting, with the primary objective of evaluating the efficacy or effectiveness of AR apps in improving patient outcomes, care processes, and learning outcomes. Of the 14 studies analyzed in this systematic review, the majority demonstrated a significant improvement in desired outcomes with the integration of AR into their workflow, suggesting that AR may have a valuable role to play in enhancing the quality of prehospital care.

AR as CDS Tools

Studies investigating the utility of AR in providing real-time CDS demonstrated a significant improvement in at least 1 outcome. AR interventions are especially effective in providing real-time decision support for MCI scenarios, enhancing both the accuracy and efficiency of triage procedures and casualty counts. AR-based remote guidance improved procedure quality for fully-trained medical students performing simulated chest thoracotomy procedures, as well as for laypeople responding to simulated childbirth. These results suggest that AR may have an important role to play in improving medical control for EMS, as AR-based feedback and guidance could greatly enhance decision-making for prehospital care providers as compared with traditional audio feedback [36-38]. Results of these studies also suggest that AR may serve a vital purpose in tactical emergency medicine scenarios, including military and law enforcement operations that could benefit from remote guidance in high-acuity scenarios [35,39]. Future research could investigate AR integration into tactical emergency medicine scenarios, such as SWAT team activations.

It is also important to note the potential integration of AR with other emerging technologies, such as artificial intelligence algorithms, which could further enhance decision support by providing predictive analytics and personalized recommendations [13,40,41]. Combining AR with wearable biometric sensors could offer real-time monitoring of vital signs, providing a context-aware decision support system that enhances situational awareness and operational efficiency [10].

AR as Training Tools

With regards to education and training, 2 of the 4 studies examining the benefit of AR in augmenting CPR training demonstrated significant improvement in CPR quality following AR intervention. These findings suggest that it may be feasible to integrate AR into CPR training. The study by Koutitas et al [23], which examined an AR-based training module for familiarization with AmBus systems also demonstrated improved task completion and enhanced comfort and familiarity with the vehicle in the AR intervention group, suggesting that AR may prove a useful adjunct to EMS companies in training new hires. Notably, some studies, that examined AR intervention in prehospital education and training modules for skills including, CPR, BLS, advanced life support procedures, and TCCC, showed no difference in performance with AR intervention. It is possible that some of these tasks, which involve a significant number of hands-on skills, were more difficult to adapt from in-person instruction to AR-based training. Future research could more thoroughly explore discrepancies in AR-based training modules among various prehospital clinical skills [42]. Furthermore, the scalability of AR training modules offers a significant advantage for widespread training initiatives, allowing consistent and repeatable training experiences across different geographical locations. This scalability is particularly beneficial for remote and underserved areas where access to high-quality training resources is limited.

Challenges of AR Technology

Overall satisfaction with AR platforms was high across the 14 studies; manuscripts that solicited user feedback found that most participants reported positive perceptions of the technology. Several common concerns emerged from this user feedback. These common concerns are summarized in Table 4.

Of greatest concern was user comfort as well as occasional unpleasant side effects associated with the use of AR. Several manuscripts indicated that wearable interventions, particularly those including headsets, were not compatible with participants who wore prescription eyeglasses. Additionally, some reported participants experiencing side effects after AR use, including dizziness, headache, and nausea. This constellation of adverse effects is collectively known as "cybersickness [43]," and has been demonstrated to impact AR, mixed reality, and virtual reality users, particularly those who are susceptible to motion sickness [44]. Future research into AR should factor cybersickness risk into study design and look to mitigate side effects. Other common concerns included the costs associated with both the purchase and maintenance of AR platforms [45], as well as inconsistent user interface and frequent technological glitches [46]. Addressing these concerns requires a multi-faceted approach [47,48]. Collaborations with manufacturers, health care providers, and end users will be crucial in creating AR systems that are not only effective but also user-friendly and economically viable [9,12]. Additionally, ongoing education and support for users can help mitigate some of the initial discomfort and resistance to new technology [49].

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Table . Summary of common concerns related to augmented reality (AR) use in prehospital care, including user comfort, user interface issues, information technology (IT) challenges, and cost.

Concern	Source
User comfort	• Headgear uncomfortable or disruptive to workflow, causes unpleasant side effects (Rebol et al, 2023 [22]; Doswell et al, 2020 [25]; Follman et al, 2019 [28]; Du et al, 2022 [29]; Follman et al, 2021 [31]; Hou et al, 2022 [32]) • AR implicated: HoloLens, Google Glass, Moverio
User interface	• User interface confusing or difficult to use or requires steep learning curve (Follman et al, 2021 [31]; Glick et al, 2021 [35]) • AR implicated: HoloLens, ReconJet
IT issues	• Poor battery life, screen glitching, application freezing (Rebol et al, 2023 [22]; Barcala-Furelos et al, 2023 [27]; Aranda-García et al, 2024 [30]; Follman et al, 2021 [31]) • AR implicated: HoloLens, ReconJet, Vuzix
Cost	• High cost of materials, setup, and maintenance (Du et al, 2022 [29]) • AR implicated: HTC VivePro

Limitations and Future Directions

This systematic review had several limitations. First, many of the included studies were of small sample size. Most studies included under 50 participants, with several included 10 or fewer, which may result in some included studies being underpowered. It is not unusual for studies investigating expensive technologies in potentially cumbersome settings to by necessity include small numbers; however, future research can prioritize adequate sample sizes to ensure robust statistical analyses. Second, our review compared studies with variable outcomes and statistical methodology and thus was not able to examine data in aggregate. A potential next step would be to conduct a meta-analysis of AR interventions in specific emergency prehospital applications, such as CPR training or MCI triage. Third, this review only included studies of AR apps in the prehospital care of adults. Future research will include inquiries into applications of AR for use with pediatric populations. Finally, a main limitation of our search approach was the potential for missed manuscripts due to not features like MeSH headers in PubMed. However, the use of broad search terms across multiple databases helped mitigate this limitation.

Conclusion

This systematic review shows the promising role of AR technology in enhancing the efficacy of prehospital emergency care. The analyzed studies, involving a total of 14 RCTs demonstrate that AR may enhance clinical decision-making and training modalities within prehospital settings. These improvements are crucial in high-stakes environments where rapid and accurate response is essential. Challenges related to technology integration, cost, and user acceptance remain. Addressing these barriers and conducting further research will be vital for realizing the full potential of AR in prehospital care delivery.

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Data Availability

This study is a systematic review, and all data analyzed are derived from previously published studies. Complete references and sources for all data used are provided within the paper, ensuring full transparency and accessibility.

Conflicts of Interest

AE serves as an advisor for MedVR Education and Apoqlar. Their products are not discussed in this paper.

Multimedia Appendix 1
Detailed search strategy across databases for identifying studies on augmented reality in prehospital emergency care.
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Multimedia Appendix 2
Systematic review form used for extraction relevant information from included papers.
[DOCX File, 23 KB - xr_v2i1e66222_app2.docx]

Multimedia Appendix 3
Bias evaluation tool questions.
[DOCX File, 17 KB - xr_v2i1e66222_app3.docx]

Checklist 1
PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) checklist.
[DOCX File, 32 KB - xr_v2i1e66222_app4.docx]

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Abbreviations

ACM: Association for Computing Machinery
AR: augmented reality
BLS: basic life support
CDS: clinical decision support
CPR: cardiopulmonary resuscitation
EM: emergency medicine
EMT: emergency medical technician
IEEE: Institute of Electrical and Electronics Engineers
MCI: mass casualty incident
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis
RCT: randomized controlled trial
TCCC: tactical combat casualty care

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Virtual, Augmented, and Mixed Reality for Motor Neurorehabilitation: Scoping Review Focused on the Role of Body Representation

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Abstract

Background: Extended reality (XR), encompassing virtual reality, augmented reality (AR), and mixed reality, is increasingly being used in neurorehabilitation to provide multisensory feedback and promote neural plasticity in sensorimotor networks.

Objective: This scoping review aimed to (1) examine how XR technologies are applied in motor neurorehabilitation, (2) explore how body representation and somatic embodiment are addressed, and (3) analyze the methodological designs of XR-based interventions.

Methods: This review was conducted in accordance with the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) guidelines, with a comprehensive search across PubMed, Embase, Scopus, and Web of Science from inception to December 2023. Eligible studies included original research involving XR-based interventions explicitly targeting neurorehabilitation. Studies related to somatic embodiment and reporting data on implementation and user outcomes were considered without date restriction. Three independent reviewers conducted screening in Covidence. The following variables were extracted: study design, participant characteristics, XR devices and software, experimentation details, treatment approaches, and evaluation methods. Methodological quality of the included studies was assessed using the Newcastle-Ottawa Scale and the Murad Scale. Findings have been presented in tabular and narrative formats.

Results: Twenty-six studies met the inclusion criteria, and these were mainly clinical trials involving patients with neurological conditions, particularly poststroke status (n=6) and spinal cord injury (n=2). Several studies provided physiological data, including electroencephalography (n=12), electromyography (n=2), magnetic resonance imaging (n=1), galvanic skin response (n=1), electrodermal activity (n=1), and motor-evoked potential data (n=1). Two studies used noninvasive brain stimulation, and another two used eye tracking. Most studies (n=17) used built-in motion sensors; however, some (n=8) analyzed the data quantitatively. Unity 3D was the most frequently used development platform (n=8). First-person (n=20) and third-person (n=2) perspectives were used, and 4 studies combined both perspectives. Interventions mainly targeted sensorimotor deficits, with improvements in motor and cognitive performance. Sixteen studies addressed body perception, focusing on limb embodiment. Questionnaires were the most frequently used evaluation tools (n=18), and 3 studies used standardized tests. Some studies (n=7) investigated body ownership under visuomotor inconsistencies with or without visuotactile stimulation. XR was primarily applied to enhance sensorimotor recovery and assess device feasibility. Few studies directly measured embodiment (n=4), ownership (n=2), or self-location (n=2). The ability of XR platforms to deliver multisensory feedback appears to facilitate sensorimotor learning and support a more accurate body schema.

Conclusions: Evidence from the studies supports the usefulness of XR in enhancing reinforcement learning and facilitating recovery in neurorehabilitation. Tailored XR approaches, which are grounded in embodiment principles and patient-specific needs, show promise for improving outcomes in neurological rehabilitation programs. The AR paradigm, which could offer several advantages, was not explored in depth, perhaps due to its difficult implementation during the period considered.

Trial Registration: PROSPERO CRD42023481092; https://www.crd.york.ac.uk/PROSPERO/view/CRD42023481092

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KEYWORDS

body representation; embodiment cognition; virtual reality; augmented reality; neurorehabilitation

Introduction

Background

Motor neurorehabilitation plays an important role in restoring movement following neurological injuries, such as stroke, spinal cord injury (SCI), and traumatic brain injury. Extended reality (XR), including virtual reality (VR), augmented reality (AR), and mixed reality (MR), has emerged in recent years as a promising tool to enhance rehabilitation by providing immersive, interactive, and customizable therapeutic environments [1]. Regarding the integration of XR in motor neurorehabilitation, questions remain about its usability and implementation in clinical practice. These immersive technologies offer possibilities for engaging patients in enriched environments that can simulate real-world motor activities and provide useful real-time feedback [2]. XR applications can support sensorimotor learning by leveraging visual, proprioceptive, and tactile cues [3]. A growing body of research has begun to explore how XR technologies can influence body representation, a key neurocognitive construct underlying motor control and recovery. Concepts, such as body schema, body image, and embodiment, are recognized as relevant to rehabilitation outcomes, especially in interventions that aim to restore motor function by altering or reinforcing body-related perceptual and sensorimotor processes [4,5]. Despite promising developments, there is a lack of methodological clarity in how XR-based interventions for motor neurorehabilitation conceptualize and implement body representation.

Contribution of the Sensorimotor System, Motor Imagery, and Cognitive Domains to Body Representation

In scientific terms, body representation comprises 2 primary modes of expression, both of which are internal to the subject: body schema and body image. Although both modes are internal to the subject, body schema can be defined as an objective representation because it is conditioned by multisensory perception, whereas body image is a subjective representation resulting from cognitive processing and emotional response [6].

While body schema has been extensively studied in relation to motor and postural outcomes or adaptations following neurological diseases, body image, referring to the subjective mental representation of one's own body, has involved the study of complex neural pathways that create a synthesis between the objective and subjective representations of the body [7].

Neuroimaging studies have identified specialized cortical areas for processing body shapes and actions, highlighting the significance of interoception alongside exteroception and proprioception for body awareness. There is evidence that the insular cortex processes interoceptive signals, thus playing a key role in determining body consciousness [8].

Despite extensive research on the integrated representation of the body, precise brain structures remain elusive. However, the extra striate body area has emerged as a neural substrate for body shape and size perception [9]. In this regard, it is worth noting that many important seminal papers on brain imaging related to body schema and body image have been produced overall and specifically in the multisensory neurorehabilitation field [6,10-14].

Proprioception, a key sensorimotor system modality, enables individuals to perceive body position and movement independently of vision. Additionally, the discovery of sensory neurons in frontal motor circuits challenges the traditional view of motor control, suggesting sensorimotor system involvement in cognitive processes [15]. The visual perception of the body and its movement involves other considerations that refer to the so-called mirror neurons. Mirror neurons, which are a part of the sensorimotor system, activate during both action execution and observation, fostering a sense of embodiment [16]. Besides proprioception, the sensorimotor system integrates information from other senses like vision and touch, enhancing body representation accuracy [17-19]. Motor skill learning alters body perception and control, and it is influenced by top-down factors and task demands [20]. Experimental findings suggest that mediated sensory perception, like mirrored hand movements, can induce abnormal body representations [19]. When sensory or cognitive deficits limit body movement in space, the contribution of motor imagery becomes important. Motor imagery is vital for cognitive body representation and is used in contexts such as rehabilitation to enhance motor skills and awareness [21]. Proprioceptive input significantly influences mental rotation, highlighting its role in motor control and spatial awareness [22].

Cognitive processes, including memory and attention, shape body representation and awareness. Brain regions like the parietal cortex integrate sensory inputs to create coherent body representations [23]. Subcortical structures like the limbic system regulate emotional responses and body memory, while brain plasticity modifies body image in response to experiences [24]. The peripersonal space surrounding the body plays a crucial role in physical interactions and self-location. The peripersonal space adapts based on experiences, technology, and social interactions, supporting bodily self-consciousness and higher-level cognition [25].

Body image construction involves emotional regulation and cognitive processes. Stress can alter body perception, while self-esteem can enhance it [26], and body dissatisfaction is influenced by factors like visual memory and inhibition [27]. Changes in body schema and distortions in body image can result from various neurological and psychiatric conditions [28]. For instance, individuals with SCI or anesthesia may continue to experience sensations related to body size, shape, and posture despite the absence of immediate sensory signals, suggesting the role of cognitive and emotional processing in body image [29]. Moreover, studies exploring body image experiences in people with SCI have revealed categories such as physical appearance concerns, negative functional features, and body disconnection [30]. Similarly, in patients with multiple sclerosis,

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higher disability levels are associated with more negative body perceptions and lower self-esteem [31].

In conditions like stroke, damage to brain areas involved in body perception and sensory processing can lead to neglect syndrome, where individuals may ignore or be unaware of one side of their body [31,32]. Moreover, phenomena like phantom limb syndrome, which is observed in amputees, and alien limb syndrome, which is seen in conditions like corticobasal degeneration, illustrate how the brain's representation of the body can persist despite physical changes or dysfunction [33,34]. Alien limb syndrome involves a dysfunction in neural circuits controlling body ownership and limb movement, resulting in distorted perceptions of the limbs and sensations of foreignness [35]. These examples highlight the intricate relationship between neurological factors and body image perception, shedding light on how changes in body schema and distortions in body image can manifest across various conditions.

Applications of VR, AR, and MR in Clinical Rehabilitation

VR, AR, and MR not only provide new ways of conducting standardized, repetitive exercises and quantitative evaluations but also enable the development of novel therapeutic approaches [36]. Applications span disparate areas with different objectives and purposes. In relation to VR, these areas include stroke [37,38], Parkinson disease [39], Alzheimer disease [40], brain injury [41,42], unilateral spatial neglect [43], and pain management [44]. VR is also used in psychiatric disorders like specific phobias [45] and eating disorders [46,47]. Reviews suggest proposing XR-based tools [42,48].

In XR technologies, the boundary between reality and simulated reality is questioned [49]. The concept of the VR continuum, introduced by Milgram and Kishino in 1994 [50], maps out a range of environments stretching from the fully real to the fully virtual [51]. On one end, we find the physical world as we know it, and on the other end, we find a completely computer-generated environment, which is commonly called VR. Between these 2 extremes lies what is defined as MR, a middle ground that includes AR, where digital content is layered onto the real world, and augmented virtuality, where elements from the real world are brought into a mostly virtual setting. VR typically refers to interactive, computer-generated 3D environments that users can explore and manipulate in real time, usually through head-mounted displays (HMDs). These devices provide stereoscopic visuals and track both head and body movements, allowing the user's perspective to shift naturally as they move. This creates a powerful sense of presence, as described by Jerald [52], and enables meaningful interaction with the virtual space. VR is now widely used across fields, such as entertainment, education, professional training, and health care [53]. While HMDs are currently the most common way to access VR, other immersive systems have also been developed. One notable example is the CAVE (Cave Automatic Virtual Environment), a room-sized installation with projected screens and motion tracking that allows multiple users to experience shared, walk-in virtual environments [54]. In contrast, Powerwall displays (large, high-resolution visualization screens) are typically associated with scientific visualization rather than immersive VR, mainly because they do not usually offer a deep sensorimotor immersion capacity. XR encompasses everything from AR and MR to fully immersive VR, acting as a "catch-all" for technologies that merge real and virtual environments in different ways. It is important to remember some basic aspects related to XR, which must be considered in rehabilitation applications. XR environments are typically characterized along the following key dimensions: immersion, presence, and embodiment [55]. These constructs, while distinct, are tightly interconnected and particularly relevant when examining the neurocognitive processes underlying motor rehabilitation. *Immersion* is the degree to which an XR system engages the user's senses, excluding stimuli from the real world. The higher the level of immersion, the better the system can simulate a convincing sensory experience [56]. Immersion can be sensory (eg, high-quality graphics and 3D sound), interactive (ability to interact with the environment), and narrative (emotional engagement with the story or context of the virtual world). A VR headset with high resolution, directional audio, and a tactile controller increases immersion compared to a 3D world displayed on a screen (even a large screen) [57]. The concept of *multisensory experience* refers to the involvement of multiple senses (sight, hearing, touch, smell, and taste) to create a more realistic and engaging XR experience. Most XR experiences focus on sight and hearing, but adding tactile (haptics), thermal, or even olfactory stimuli can amplify the sense of presence and realism. While immersion refers to the degree of sensory stimulation provided by the XR system, its multisensory nature enhances the user's engagement by stimulating multiple perceptual channels simultaneously. However, the sense of being in the virtual environment (presence) is also deeply intertwined with the sense of being the virtual body (embodiment) [58]. *Embodiment* is the sense of identification with a virtual body or avatar in the XR environment. This can be particularly useful in applications like rehabilitation, training, or neuroscience experiments. It can be influenced by the consistency between movements of the real body and those of the virtual body, avatar customization, and sensory feedback (eg, visual and tactile). This kind of view perspective can surely affect the embodiment level, but it is still not clear which one offers a better embodiment [59,60]. *Presence* issues refer to the subjective feeling of "being there" in the virtual environment, as if it were real. Presence is affected by immersion, and it occurs when the user's brain accepts the virtual environment as a plausible reality, making the user forget that they are in a physical space. It can be affected by graphics quality, the realism of interactions, and latency. Moreover, it is associated with many other variables and is a constantly researched metric [5,59,61-63]. All the reported factors (multisensory experience, embodiment, and presence) are part of the concept of immersion.

Cyber sickness is a possible side effect of the use of XR technologies that must be considered, especially when used by subjects with disabilities. It arises from a conflict between sensory signals, such as when vision perceives movement in the virtual environment, but the body and inner ear remain static. Its symptoms are nausea, dizziness, headaches, visual fatigue, and disorientation. We can mitigate the risks of cyber sickness by improving frame rates, reducing latency, avoiding some

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particular visual movements, and designing more natural interactions (eg, allowing the user to "walk" physically instead of moving via controllers) [64]. Latency, often referred to as "motion-to-photon latency," describes the delay between a user's physical movement and the corresponding update in the XR environment [65]. When latency exceeds approximately 20 - 30 milliseconds, it becomes perceivable and may cause sensory conflicts [35,48,49].

Scope of the Review and Paper Organization

The research objectives include reviewing the literature on body representation and XR applications in patients with neurological conditions and focusing on technical aspects to propose innovative rehabilitation tools. An analysis of the literature found that in the last decades, several reviews concerning new technologies in neurorehabilitation have been published [66], with some studying the effects on multiple cognitive domains [67] or addressing particular conditions (eg, poststroke) [68]. On the other hand, the relevance of the body image concept and its potential to bring about significant changes in therapy have not yet been comprehensively reviewed. This introduces a gap in understanding the state of research regarding the use of novel adjunctive technology for beneficial intervention in the neuromotor domain and body image representation. To address this gap, we have conducted a scoping review aimed at providing current knowledge on VR, AR, and MR solutions for neurorehabilitation centered on the body image concept. Unlike previous reviews, which tended to focus on specific dimensions of body image disturbance in neurological rehabilitation, our work provides a comprehensive technological perspective. By detailing the XR devices, interaction modalities, and implementation settings used across studies, this review offers a practical resource for researchers aiming to explore or develop novel XR-based interventions. Our goal is to bridge the gap between clinical insight and technological implementation, enabling more informed decisions when selecting or designing XR solutions for body image rehabilitation in neurorehabilitation contexts.

This review aimed to (1) identify how VR, AR, and MR are used in motor neurorehabilitation contexts; (2) analyze how body representation is addressed; and (3) analyze the methodological approaches used in XR interventions. Regarding paper organization, the next section outlines the methods used, including the search strategy. Subsequently, the outcomes of the steps are presented, along with an analysis of various aspects of the research selected and retrieved. This is followed by a comprehensive discussion that reports the principal findings of the study based on an analysis of the results. Lastly, in the conclusion, we provide a summary of the work's content and its relevance, and offer perspectives for future studies and insights.

Methods

Search Strategy

The PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) guidelines were adopted [69]. The PRISMA-ScR checklist is provided in Checklist 1. The research protocol was registered by GD in the PROSPERO public registry (ID: CRD42023481092) before data extraction. Some changes were made to the registered research protocol. The objective was to critically analyze the existing literature on XR applications related to motor problems and somatic representation, which proposed new tools and experiments. This review was performed by searching 4 different electronic databases: PubMed, Embase, Scopus, and Web of Science. The search across the 4 databases was conducted on December 7, 2023, without any time limitations.

Final Search Strategy Used in Each Database

For the development of the search strategy, several meetings were held with neurologist colleagues from the Spinal Cord Injuries Unit, Neuroscience Department, Pisa University Hospital, who are some of the authors of the research (CD and PB). The following groups of concepts were considered:

1. Target population: (Neurologic* OR Poststroke OR Post-stroke OR Post Stroke OR Stroke OR Brain Surgery OR Cerebral Palsy OR Paresis OR Spinal Cord Injury)
2. Body image and associated concepts: (Body Scheme* OR Body Imag* OR Body perception OR Dismorphism OR Bodily Self OR Bodily Self Consciousness OR Body Illusion* OR Body Matrix OR Body Model Theory OR Body Representation OR Body Swapping OR Embodiment OR Embodiment Cognition OR Ownership Illusion*)
3. Expositions and computer science concepts: (Virtual Reality OR Augmented Reality OR Mixed Reality OR 3D OR Tridimensional OR Avatar OR Virtual Embodiment OR Virtual Reality Reflection Therapy)
4. Experimental intervention outcome: (Neurorehabilitation OR Motor Recovery OR Motor Rehabilitation OR Action Understanding).

From these groups of concepts, the following updated query was developed: (Neurologic* OR Poststroke OR Post-stroke OR Post Stroke OR Stroke OR Brain Surgery OR Cerebral Palsy OR Paresis OR Spinal Cord Injury) AND (Body Scheme* OR Body Imag* OR Body perception OR Dismorphism OR Bodily Self OR Bodily Self Consciousness OR Body Illusion* OR Body Matrix OR Body Model Theory OR Body Representation OR Body Swapping OR Embodiment OR Embodiment Cognition OR Owner-ship Illusion*) AND (Virtual Reality OR Augmented Reality OR Mixed Reality OR 3D OR Tridimensional OR Avatar OR Virtual Embodiment OR Virtual Reality Reflection Therapy) AND (Neurorehabilitation OR Motor Recovery OR Motor Rehabilitation OR Action Understanding).

Eligibility and Exclusion Criteria, Study Selection, and Data Extraction

Mendeley Reference Manager was used to identify and eliminate duplicate records within the library. After removing duplicates, 3 authors (OC, MM, and DM) independently evaluated titles and abstracts (n=98) based on the eligibility criteria. Articles were included if they involved XR interventions explicitly described as being for neurorehabilitation, reported user uptake data, reported implementation data, and were published in the peer-reviewed literature.

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The articles selected by the 3 authors were independently read in full during the second screening phase to determine the final set of articles to be included in the review. In the case of conflicts, the 3 authors discussed the findings together, and if an agreement was not reached, the other authors provided the final judgment. The exclusion criteria were as follows: generic studies (ie, those addressing broad or nonspecific topics without a focused investigation into XR tools or original findings), editorials, reviews, studies that did not involve XR tools, and studies not available in English.

Data Synthesis

A qualitative synthesis was conducted, in line with the PRISMA guidelines (PRISMA-ScR), to examine and compare methodological approaches across studies using XR for motor neurorehabilitation. All included studies were analyzed using a standardized data extraction form that captured study design, population characteristics, XR technology type, intervention protocol, outcome measures, and references to body representation (Multimedia Appendix 1). Studies were grouped by technology type and intervention context. When sufficient homogeneity in outcome measures (eg, motor performance scores and embodiment questionnaires) was present, basic quantitative aggregation (eg, frequency of use and effect direction) was performed descriptively. However, no formal meta-analysis was conducted due to high variability in study design, outcome measures, and intervention protocols.

Study Quality

To assess the quality of each study, the Newcastle-Ottawa Scale (NOS) was used. The NOS is a collaboration between the University of Newcastle, Australia and the University of Ottawa, Canada. It has been developed to assess the quality of nonrandomized studies. A “star system” is used, and a study is judged on 3 perspectives: the selection of the study groups, the comparability of the groups, and the ascertainment of either the exposure or the outcome of interest for case-control or cohort studies [70]. Each study was assigned a score of up to 9 stars, except for cross-sectional studies, which could receive a maximum of 8 stars.

For case report studies, we used a dedicated scale published by Murad et al [71], which assigns a maximum of 8 points to each study. Case reports and case series are uncontrolled study designs, which are known to have an increased risk of bias. This guide provides a framework for evaluating the methodological quality of case reports and case series based on the domains of selection, ascertainment, causality, and reporting, and provides signaling questions to aid evidence-based practitioners and systematic reviewers in their assessment. The tool for evaluating the methodological quality of case reports and case series is based on leading explanatory questions concerning the following aspects of a clinical trial: (1) Selection (Does the patient(s) represent(s) the whole experience of the investigator (center) or is the selection method unclear to the extent that other patients with similar presentation may not have been reported?); (2) Ascertainment (Was the exposure adequately ascertained? Was the outcome adequately ascertained?); (3) Causality (Were other alternative causes that may explain the observation ruled out? Was there a challenge/rechallenge phenomenon? Was there a dose-response effect? Was follow-up long enough for outcomes to occur?); and (4) Reporting (Is the case(s) described with sufficient details to allow other investigators to replicate the research or to allow practitioners to make inferences related to their own practice?) [71].

These assessments were integrated into the synthesis to confirm the strength and reliability of the findings, and the scores and characteristics of the studies are reported in Multimedia Appendix 1.

Results

Search Results and Study Characteristics

From PubMed, 87 results were initially obtained. After applying the electronic database filter for only those articles that had the keywords in their titles and abstracts, 8 articles were identified. Using the Embase search engine, we obtained 14 articles. Querying the Scopus search engine with the search string, we identified 581 records (“all field” search). The filter “title and abstract” was then selected, and the search was repeated by using “article” and “computer science” as filters. At this point, 59 articles from Scopus were identified. Using the Clarivate Web of Science archive, we identified 29 records. The PRISMA flow diagram is presented in Figure 1.

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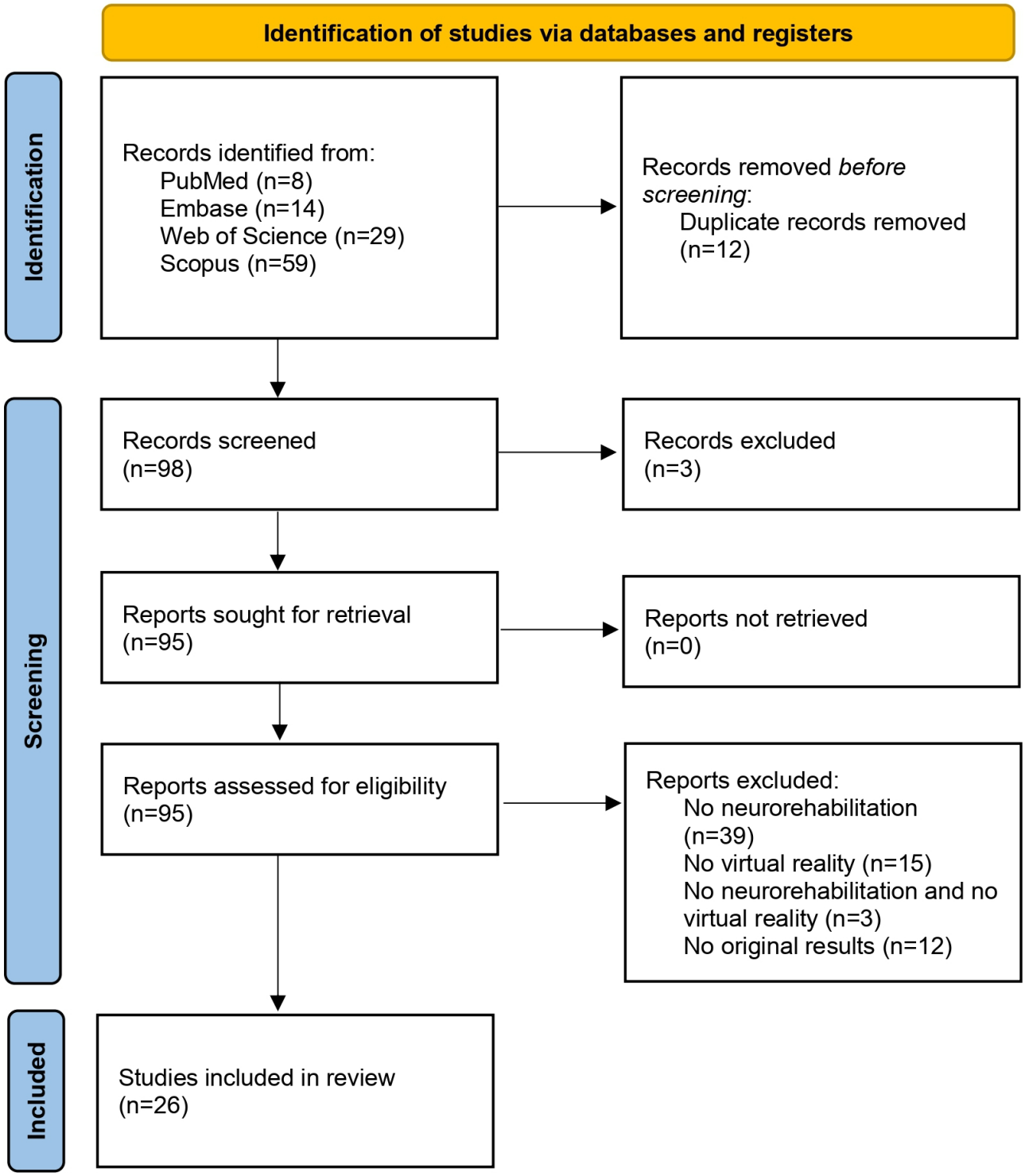
Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 flow diagram of article selection.



Out of the total 110 records obtained from the 4 search engines, 12 duplicate records were removed, resulting in 98 records. Three records were excluded as they were articles related to proceedings, and the remaining records were scientific papers, either experimental or based on systematic or narrative literature reviews (Figure 1). After screening the full text and applying the exclusion criteria, 26 articles were included in the review. By the end of the identification process, 76% (84/110) of articles in the initial set were excluded.

Geographical and Timeline Distribution

The articles included in this review involved studies carried out in Italy (n=6), Switzerland (n=5), Japan (n=3), China (n=2), Portugal (n=2), United Kingdom (n=1), Spain (n=2), United States (n=1), Mexico (n=1), New Zealand (n=1), Korea (n=1), and Brazil (n=1). Table 1 presents the geographical and timeline distributions of the studies. Research has increased in the last 5 years, with over 80% (21/26, 81%) of studies being published from 2019 to 2023 (Table 1).

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Table . Geographical and timeline distribution of the studies included in the review (N=26).

Country	Year									Total per country
	2013 (n=1)	2016 (n=1)	2017 (n=2)	2018 (n=1)	2019 (n=2)	2020 (n=3)	2021 (n=4)	2022 (n=5)	2023 (n=7)	
Italy	0	0	0	1	0	1	1	1	2	6
Switzer-land	0	0	1	0	0	0	1	2	1	5
Japan	0	0	1	0	1	0	1	0	0	3
China	0	0	0	0	0	0	0	0	2	2
Portugal	0	0	0	0	0	0	0	1	1	2
United Kingdom	0	0	0	0	0	0	0	0	1	1
Spain	1	0	0	0	1	0	0	0	0	2
United States	0	0	0	0	0	0	0	1	0	1
Mexico	0	0	0	0	0	0	1	0	0	1
New Zealand	0	0	0	0	0	1	0	0	0	1
Korea	0	0	0	0	0	1	0	0	0	1
Brazil	0	1	0	0	0	0	0	0	0	1

Study Design and Population

Among the 26 studies analyzed, variability was observed in the sample size of participants and in the type of participants involved in the analysis. One study included a single patient [72], and another study involved an analysis of 1 patient and 5 healthy male control participants [73]. The largest sample (113 healthy participants and 16 patients who had experienced stroke) was noted in the study by Dong et al [74]. The upper limbs and hands were the most frequently evaluated body parts (n=19), and 3 studies assessed the application of VR to the entire body. Two studies involved children. The study by Phelan et al [75] included 3 boys and 5 girls with upper limb motor impairment (mean age of 13 years), and the study by Garcia-Hernandez et al [76] included 19 children with cerebral palsy (mean age of 8 years). Of the 26 studies, 12 included only healthy participants, 11 included only patients, and 3 included both healthy participants and patients. Only 2 articles involved studies that could be considered to have a case-control design. The main pathological conditions identified were poststroke status (n=6) and spinal trauma (n=2).

Intervention Evaluation Studies and Outcome Measures

Among the selected studies, 16 explicitly stated that they involved body perception. Most studies (n=14) investigated the embodiment of virtual representations of the limbs, and in particular, 6 studies focused on the sense of agency toward virtual limbs. Matsumiya [77] explicitly considered motor control.

Administration of questionnaires represented the most used method for evaluating the usefulness of the proposed systems (18 out of 26 studies). Three studies indicated the use of standard assessment systems or those derived from standards, such as the Box and Block test. Caola et al [78] explored whether it is possible to induce a sense of body ownership over a virtual body part during visuomotor inconsistencies, with or without the aid of concomitant visuotactile stimulations. The study enrolled 45 healthy participants. A small vibrator was placed in the middle of the dorsal part of the participant's right hand and controlled via an Arduino board. From a first-person perspective (FPP), the participant watched a virtual tube moving or an avatar's arm moving, with or without concomitant synchronous visuotactile stimulations on the hand. Three different virtual arm or tube speeds were investigated while all participants kept their real arms still. The primary result from this research was that it is feasible to generate a feeling of ownership over a virtual body part, even in the presence of a significant discrepancy between the real and virtual limbs' visual and motor aspects [78], and the findings were derived from a questionnaire-based approach [79]. Some studies indicated the extraction of indices from physiological data, such as electroencephalography (EEG; n=12), electromyography (EMG; n=2), magnetic resonance imaging (MRI; n=1), galvanic skin response (n=1), electrodermal activity (n=1), and motor-evoked potential data (n=1). The manual controllers provided with VR systems can easily be used to detect movement characteristics, with 4 studies using indices derived from their data. Gaze analysis was not widely used among the selected studies, appearing in only 2 studies. In an experimental study, Kaneko et al [80] clarified the effect of kinesthetic perception illusion induced by visual stimulation (KINVIS) on upper limb motor function and the relationship between motor function and resting-state brain networks. Eleven patients with severe upper limb paralysis were enrolled, and functional MRI was used to evaluate motor function and resting-state brain functional connectivity. The cognitive phenomenon of KINVIS was

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described as the feeling of one's body moving during sensory input, even though the body is actually in a resting state. The approach involved a FPP and an AR system with monitors. The participants received visual stimulation for 20 minutes together with neuromuscular electrical stimulation. The patients were seated on a chair with their forearms on a table. The hand movement of the unaffected side was recorded before the intervention. The movement task involved hand opening and closing. This task was executed using the unaffected side, and the recording was flipped to reflect the movement of the affected side. The results of motor function (Fugle-Meyer Assessment) and spasticity (Modified Ashworth Scale) showed significant improvement following the intervention. Assessment and evaluation were carried out using the Action Research Arm Test, the Box and Block Test, the Motor Activity Log, and MRI data analysis [80]. The selected studies were quite heterogeneous, and thus, there were differences in the types of evaluation tools. However, given the extensive use of self-report tools, such as questionnaires [81], there is still no clarity regarding the objective and standardized evaluation of the effectiveness of XR use. Inamura et al [82] determined the feasibility of a VR system (whether it has enough effect on the sense of agency and sense of ownership) in healthy participants before conducting experiments in patients with phantom limbs. The Kinect V2 VR system was used. In this system, a virtual avatar performs a motion identical to that of the participant using a motion-capture device. The participant wore a 3D HMD to experience seeing through the eyes of the avatar. Six conditions of avatar representation were used: 2 arms (normal human arm and robot arm) and 3 lengths of each arm (short, medium, and long). The participant executed elbow flexion-extension movements of the right arm, which caused the same movements in the VR avatar's arm. The findings indicated that the perceived length of the arm was altered based on the displayed arm's length within the VR setting. Through analysis of questionnaire responses, it was determined that there was no adverse impact on the sense of agency. Additionally, it was observed that the sense of ownership was stronger when participants viewed a normal human arm than when they viewed a robot arm. The evaluation was carried out using a questionnaire and gesture data analysis. After the induction movement, the subjective sense of the length of the right arm was measured by a pointing gesture of the left hand [82]. Pozeg et al [83] investigated changes in body ownership and chronic neuropathic pain in patients with SCI using multisensory own body illusions and VR. Their study enrolled 20 patients with SCI and paraplegia and 20 healthy control participants. The HMD used showed a real-time (or delayed) video of dummy legs from a distance and angle that corresponded to the participant's first-person viewpoint. The findings revealed that individuals with SCI had reduced sensitivity to multisensory stimuli that generated an illusion of leg ownership in comparison to those without such injuries (healthy controls). Furthermore, the sense of leg ownership diminished over time following SCI. Interestingly, there were no discernible distinctions between the groups in terms of overall body ownership, as assessed by a full-body illusion (FBI). The assessment and evaluation methods were as follows: the virtual leg illusion was assessed with a 9-item questionnaire adapted from body illusion studies, the FBI was assessed with a 7-item questionnaire, and actual neuropathic pain was assessed with a visual analog scale [83]. The VR, AR, and MR tools were mainly used to improve sensorimotor function in adults with neurological disorders and to test the feasibility of the devices. While body representation may be activated during the use of these tools, of the 26 included studies, 6 had an outcome measure on embodiment, 5 had an outcome measure on ownership, and 2 had an outcome measure on self-location perception.

Quality Assessment

In the quality assessment, 13 studies obtained the maximum score, and the remaining studies scored slightly below the maximum score. However, in 1 study, the results were not adequately reported [84]. The main reason for not obtaining the maximum score was related to the limited sample size and inadequate reporting of the results. However, it is important to emphasize that a large proportion of the studies considered were feasibility or usability studies.

XR Technologies and Technical Details of the Hardware and Software

In the last 2 decades, there has been a shift from complex and bulky systems that require high-performance computers to more affordable and agile alternatives. The emergence of budget-friendly XR devices, such as Oculus Rift and HTC Vive, has undeniably propelled research involving the use of VR technologies. Among the examined studies, 7 used Oculus Rift (Dk1 and Dk2), 3 used the more recent and portable Oculus Quest 1 and 2, 6 used HTC Vive, 1 used other devices (typically older and more expensive), 1 used Valve Index, and 6 did not specify the system used. Two studies used standard, large monitors instead of HMDs, and although they were not immersive, the modality of the experiment shared many similarities with the others. Thus, they were included in the study list. Camardella et al [85] showed the design, implementation, and first evaluation of a gaming scenario for the upper limb rehabilitation of children with cerebral palsy, using one of these recent devices. The experiment was developed with 8 healthy participants (upper limb), and it involved the use of VR in the FPP with Oculus Quest 2. In this case, the VR environment depicted a magical training ground for wizards, surrounded by mountains and trees, with a large rune on the floor marking the spell-casting area. Players used their index finger as a wand to draw symbols in the air, casting spells at enemies. The accuracy of symbol drawing determined spell potency, with reference to a 2D sample provided. Two custom lightweight haptic thimbles provided tactile feedback. The assessed conditions included speed reference presence and feedback type (haptic or visual) related to tracking velocity. Preliminary examinations conducted on these healthy participants revealed that the introduction of haptic feedback did not notably change the perception of absolute speed or the capability to uphold a steady self-selected reference speed. Nevertheless, when participants were directed to adhere to a predetermined reference speed, the incorporation of haptic feedback improved performance by enhancing smoothness and diminishing speed-tracking errors. However, it is worth noting that only smoothness demonstrated a statistically significant

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improvement. The evaluation was carried on through the analysis of a dataset built using the recorded hand speed as a feature [85]. In general, these devices use hand trackers for navigation within the virtual space. However, only 5 studies explicitly mentioned the use of hand trackers [62,73,86-88]. Fregna et al [86] chose to use the optical-based hand tracking system embedded in Oculus Quest 2. In 3 studies, the authors reported using Microsoft Kinect for interaction with the virtual scene [5,76,82]. This confirms that this device, which was originally created for video games and had very little success in its domain, found new life in the research field worldwide. Heinrich et al [87] reported the use of the Leap Motion device, which is smaller than the Kinect device. Llobera et al [73] opted for an InterSense 6-degree wand device. In VR systems, users can experience either a first-person or third-person view of the synthetic world around them (where they see their avatar). Most of the identified studies (n=24) exclusively used the FPP, which is also referred to as the first-person view. Tambone et al [89] and Borrego et al [5] conducted a comparison between the FPP and first-person view, noting a higher level of embodiment in the first mode. Song et al [90] induced a third-person perspective full-body illusion (TPP-FBI) with VR in 19 patients with stroke. The study used the TPP Valve Index VR headset plus controllers in the following 4 experimental conditions: synchronous visual-tactile stimulation on the back, synchronous visual-tactile stimulation on the arm, nonsynchronous visual-tactile stimulation on the back, and nonsynchronous visual-tactile stimulation on the arm. The experimenter randomly touched the participant's back or arm with a physical bar. In synchronous conditions, virtual and physical bar stimulation matched temporally and spatially. The findings demonstrated that VR could trigger the sensation of ownership of a TPP-FBI in patients with stroke, akin to how it does in healthy individuals, through synchronous visual-tactile stimulation of a specific body part (the back or upper limb). Furthermore, it was observed that stimulating the back could evoke a more pronounced sense of a TPP-FBI compared to stimulating the affected upper limb. This suggests that for patients with stroke experiencing limb dysfunction, stimulating the back may be more effective in inducing a robust sense of ownership from a TPP. In this study, questionnaire scores reflected the subjective experience of the participants, and self-location drift values reflected the objective self-location perception [90]. To provide feedback that is crucial for creating an illusion, Pais-Vieira et al [72] used a custom-developed thermal tactile sleeve. Moreover, Shokur et al [91] adopted a tactile t-shirt equipped with eccentric mass vibrators, and Matsumiya et al [77] used a Phantom Force feedback device. The remaining studies did not specify the use of special feedback devices. Five studies incorporated EEG for recording brain responses during experiments: Pais-Vieira et al [72] and Batista et al [92] used a Brain Product GmbH EEG system, Lim et al [93] used a Wearable Sensing device, and Llobera et al [73] and Sanford et al [94] used a g.USBAmp system for recording both EEG and EMG. Two studies used transcranial stimulators for different purposes: Buetler et al [88] used them for detecting motor responses, and Lim et al [93] used them for enhancing a virtual hand illusion. Some studies used other kinds of devices for the experiments: Wenk et al [62] and Matsumiya et al [77] used an eye tracker, and Tambone et al [89] used an additional OLED display.

Most studies did not specify the 3D engine used. However, 8 studies explicitly claimed to have used Unity 3D [5,62,74,76,84,85,89,92], and only 1 study mentioned the use of Unreal Engine [75]. In the areas of the research and development of XR applications for rehabilitation, Unity 3D stands out as the preferred platform over Unreal Engine for several reasons. First, Unity is widely regarded for its accessibility and ease of use. Its gradual learning curve and extensive documentation make it particularly appealing to developers and researchers, even those without a strong background in gaming or advanced graphics. The scripting process in Unity, which is based on C#, is simpler compared to Unreal's reliance on C++, further lowering the barrier to entry. Additionally, Unity's flexibility across mobile devices and AR platforms is a major advantage. It offers native support for a wide range of AR devices, including HoloLens, Magic Leap, and various mobile headsets, through seamless integration with tools like ARKit and ARCore. This streamlines development for projects that aim to reach a diverse array of compatible devices, ensuring greater accessibility for end users. Unity also benefits from its strong presence in academic and research communities. Its ecosystem includes a wealth of third-party plugins and libraries tailored for scientific and rehabilitation applications, such as Vuforia, MRTK for HoloLens, and other medical AR solutions. These resources make it easier to rapidly prototype rehabilitation systems and integrate advanced tools for motion analysis and interaction. Finally, cost and licensing considerations play significant roles. While Unreal excels in delivering high-quality graphics for video games and advanced media, Unity is often more budget-friendly for small research groups or projects that do not prioritize cutting-edge visual fidelity. This affordability makes it an attractive option for academic and clinical research settings.

As for other additional software, MakeHuman, which was cited by Wenk et al [63] and Odermatt et al [95], is widely used for avatar creation in XR applications. Multimedia Appendix 1 summarizes the main characteristics of the studies and the XR tools included in this review in the order of the year of publication.

Discussion

Summary of Evidence

Following a meticulous screening process, 24% (26/110) of studies met the inclusion criteria, signifying a reasonable interest in this area. Notably, over 80% (21/26, 81%) of the studies were published within the past 5 years, indicating a recent surge in research attention.

Geographically, the studies were predominantly conducted in Italy, Switzerland, and Japan. They covered a diverse array of neurological conditions, including poststroke rehabilitation, spinal trauma, cerebral palsy, and others. Notable contributors to this body of research include studies by Phelan et al [75], Garcia-Hernandez et al [76], Tambone et al [89], Borrego et al

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[5], Pais-Vieira et al [72], Shokur et al [91], and Matsumiya et al [77].

Interestingly, the assessment methods used varied widely across studies. Quality assessment revealed that the limitations of the included studies primarily stemmed from issues such as small sample sizes and inadequate reporting of results. It is worth noting that a significant portion of the included studies focused on feasibility and usability rather than strictly efficacy.

There is an ongoing debate in motor rehabilitation using XR regarding the optimal perspective (FPP or TPP). Current research suggests that each perspective offers distinct advantages depending on the context and desired outcome [5,83,89]. Studies have shown that the FPP generally enhances the sense of embodiment and self-presence, as it aligns the user's visual perspective with their actions, fostering a stronger connection to the virtual avatar [5,83,86,88,95]. This may be beneficial for tasks requiring fine motor skill retraining or when the goal is to replicate natural movements. However, some studies have suggested that the TPP can also provide a comparable level of embodiment if the user identifies closely with the avatar [61]. The TPP may offer advantages for tasks requiring spatial awareness or understanding the body's overall posture and movement. For example, observing an avatar from behind can provide clearer feedback on errors in form during rehabilitation exercises. This can be particularly useful in therapies targeting balance or coordination. The effectiveness of the FPP versus the TPP often depends on the specific rehabilitation task and individual needs. For instance, patients recovering from conditions that impair body awareness might benefit from the external feedback provided by the TPP, while others might achieve better outcomes with the immersive nature of the FPP. Given the mixed findings, a hybrid approach combining both perspectives or tailoring the choice based on the user's progress and preferences might be the most effective strategy. Borrego et al [5] compared the experience of embodiment and the sense of presence in patients who have experienced stroke and healthy subjects, using both the FPP and TPP. The results indicated that the FPP enhances the sense of embodiment, while the TPP improves the awareness of global movement.

For feedback, some studies used custom devices like thermal tactile sleeves, tactile t-shirts, and force feedback devices [72,77,89,91]. Five studies recorded brain responses using EEG, while others used transcranial stimulators, eye trackers, and additional displays [72,88,89,92-94]. Haptic feedback plays a crucial role in XR systems for motor rehabilitation by enhancing the user's ability to understand and control their movements through tactile and force-based signals. This interaction not only helps patients correct their motor patterns in real time but also boosts their motivation, as the tactile sensations make rehabilitation more engaging and rewarding. Moreover, haptic devices enable the realistic simulation of object manipulation, providing a safe environment to practice practical and fine motor skills. By integrating tactile feedback with visual and auditory stimuli, haptic systems create a cohesive multisensory experience that strengthens the user's sense of presence and embodiment within the virtual environment. This sensory coherence fosters the illusion that the user's virtual body is an extension of their physical self, which is crucial for stimulating brain plasticity and supporting motor recovery. While the implementation of haptic feedback has some challenges, such as cost, complexity, and the need for precise calibration, its ability to deliver immersive and effective therapy makes it a valuable component of XR-based rehabilitation systems. Bortone et al [96,97] showed that haptics can enhance the involvement and engagement of patients, provide congruent multisensory afferent feedback during motor exercises, and benefit from the flexibility of XR in adapting exercises to the patient's needs. Rätz et al [98] developed and tested a rehabilitation device for the upper limbs that uses haptic feedback across the entire hand. Patients with a history of stroke and therapists who tested the device appreciated its ability to provide realistic haptic interaction, which is beneficial for recovering motor skills and enhancing the transfer of skills acquired to daily activities.

Comparison to Prior Work

The body of literature on the use of XR technologies in neurorehabilitation reflects a diverse array of findings and perspectives, and this scoping review sheds light on both the promises and challenges of integrating this innovative technology into clinical practice [42,48].

Ventura et al [84] conducted a systematic review that underscored the potential of body ownership illusion through VR in limb rehabilitation after stroke, highlighting its role in accelerating motor recovery by fostering a sense of embodiment [99]. This finding resonates with embodied cognition theories, which emphasize the reciprocal relationship between bodily states and cognitive functions, and this is particularly evident in language processing among individuals with neurological disorders [100]. Leeb and Pérez-Marcos [101] further explored the synergies between brain-computer interfaces and VR, highlighting their transformative potential in redefining neurorehabilitation paradigms by integrating motor-cognitive training with evidence-based neuroscience principles. In a meta-analysis, Maier et al [102] delved into the comparative efficacy of specific VR and nonspecific VR systems for upper limb rehabilitation after stroke, revealing that specific VR systems tailored explicitly for rehabilitation yielded superior outcomes compared to nonspecific VR systems [102]. These findings underscore the importance of designing VR interventions that are specifically tailored to address the unique rehabilitation needs of patients with neurological conditions. Moreover, immersive VR environments have emerged as promising tools for alleviating pain and modulating body perception, offering novel therapeutic avenues for managing conditions characterized by distorted body image [103,104]. Perez-Marcos et al [105] emphasized the role of VR in empowering patients through engaging and motivating training approaches, integrating motor-cognitive training with evidence-based principles to foster self-management and ownership of the rehabilitation process. While the potential of VR in neurorehabilitation is vast, Tieri et al [49] cautioned against overstating its superiority over conventional rehabilitation techniques, highlighting the need for a nuanced understanding of its efficacy across diverse patient populations and clinical contexts. Similarly, Dieguez and Lopez [106] underscored the importance of clinical reporting in comprehensively understanding abnormal body representations

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in neurological disorders, paving the way for targeted interventions informed by empirical evidence. Furthermore, Pulay [107] proposed leveraging eye-tracking and EMG devices in VR to facilitate cognitive and motor development in children with severe physical disabilities, offering a glimpse into the transformative potential of technology-assisted interventions for enhancing rehabilitation outcomes. In parallel, Christ and Reiner [108] explored the theoretical underpinnings and clinical applications of rubber hand and virtual hand illusions, offering insights into their implications for rehabilitation. Additionally, Hesse et al [109] traced the evolution of robotic devices for motor rehabilitation, highlighting their role in delivering intensive and task-specific therapy approaches for stroke and spinal cord injuries and thereby opening new vistas for optimizing motor recovery outcomes.

Williamson et al [1] investigated the psychological impact of XR interventions in SCI rehabilitation. Their findings suggest that XR-based therapies offer psychological benefits, including enjoyment, relaxation, and positive distraction. The review concluded that immersive interventions show potential for supporting psychological well-being during SCI rehabilitation. Lu et al [110] evaluated the integration of 3D and 4D digital human modeling with XR across 16 studies addressing conditions such as neglect, anorexia nervosa, bulimia nervosa, and type 2 diabetes. The results indicated improvements in functional, physical, psychological, and overall health outcomes. Nonetheless, the authors emphasized the need for larger sample sizes, longer-term follow-up, and standardized outcome measures to better assess the reliability and efficacy of these interventions. Previous reviews explored the use of XR in neurological disease management and psychological rehabilitation, emphasizing its role in the treatment of chronic conditions and the improvement of psychological health. Some authors [111] explored how XR technologies could reshape the treatment of neurological diseases, proposing that XR may offer innovative pathways for patient care and rehabilitation. The article highlighted the potential of XR to revolutionize treatment approaches for neurological diseases. Chenais and Görgen [112] provided an overview of current uses and future directions of immersive interfaces in clinical settings. Their review highlighted how these technologies might enhance both patient engagement and therapeutic outcomes while calling for further investigation to optimize their clinical utility. Previous literature reviews have focused on the application of XR in neurorehabilitation and highlighted its potential, but have noted the need for further efficacy research. Schuermans et al [113] conducted a systematic review on XR-supported rehabilitation and injury prevention in musculoskeletal contexts, finding added value in both sports injury prevention and recovery. Figeys et al [114] assessed MR interventions in acquired brain injury rehabilitation, noting encouraging outcomes in areas such as upper limb motor function, gait, cognition, and lower-limb mobility. However, they also pointed out the early-stage nature of much of the research, with many studies still at the prototype stage. Taghian et al [115] examined VR/AR applications in biomedical engineering, highlighting their use in fields such as rehabilitation. Their review emphasized the transformative potential of VR/AR technologies while stressing the importance of continued research to unlock their full benefits.

Compared with previous work, this scoping review focused more on technical aspects to propose innovative rehabilitation tools. Overall, the review underscores the burgeoning interest and promising potential of XR in neurorehabilitation while also advocating for more standardized evaluation methods to ensure robustness and comparability across studies.

Strengths and Limitations

This review captured a broad range of populations and health care providers across several countries. To ensure comprehensive coverage, multiple databases were searched without time restrictions. Despite the methodological rigor applied, several limitations should be acknowledged. Important differences were observed among the studies reviewed, including variations in sample size, duration of follow-up, treatment protocol, and study design. Variability in the sample population, particularly in terms of demographics and pathology, was a significant limitation. Moreover, there were limitations related to heterogeneity in treatments that resulted from variations in methodology, duration, and adherence to standard protocols, which consequently introduced uncertainty in the analysis. The absence of comparison or control groups in some studies might have affected the validity of the results. Moreover, the research had a wide scope. It was not possible to conduct a comprehensive outcome analysis because of the heterogeneity of the included research. There should be more specific and focused research questions geared toward evaluating outcomes, more evidence, and more consistent measures, and a systematic review and meta-analysis would be a valuable addition to the literature. The purpose of this literature review was to provide a broad overview of studies that adopted XR in the field of functional and cognitive neurorehabilitation, using the concept of body representation in its various forms.

While the review encompassed a comprehensive search across major electronic databases, the exclusion of other databases and gray literature may have overlooked relevant studies. Moreover, limiting the analysis to English-language articles potentially excluded methodologically robust studies published in other languages, leading to information loss.

Conclusions

This review enabled a critical evaluation of evidence and identification of knowledge gaps [116]. Through repetitive, task-specific training and reinforcement learning mechanisms, XR interventions deliver personalized and engaging rehabilitation approaches [116]. The use of animated avatars further supports motor learning via mirror neuron activation [117]. The degree of immersion, determined by sensory and motor engagement, shapes a user's sense of presence, bodily ownership, and agency within the virtual space [49,118], fostering deeper involvement in rehabilitation tasks and potentially improving motor and cognitive outcomes [49].

Nevertheless, several limitations remain. Few reviewed studies addressed cybersickness, and only a minority examined the integration of AR technologies, which may partially mitigate such effects [60]. AR offers unique advantages for poststroke rehabilitation by leveraging familiar environmental cues and facilitating the transfer of acquired skills to daily activities.

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Integrating virtual elements into real-world settings enhances embodiment, motor control, and coordination while maintaining the natural context of rehabilitation exercises and promoting engagement [63].

Recent research highlights the potential of "AR pass-through" modes available in new-generation headsets (eg, Oculus Quest 3 and Apple Vision Pro), which allow patients to perceive their real environment while interacting with virtual elements [98,114]. This continuity between real and virtual contexts reduces spatial disorientation and cybersickness, improving safety and comfort during rehabilitation. Moreover, AR enables direct interaction with real objects, eliminating the need for complex haptic feedback and simplifying system design without compromising functionality [119,120].

Overall, AR tends to induce less cybersickness than fully immersive VR because it preserves visual access to the real environment and reduces sensory conflicts. However, factors, such as headset weight, rendering latency, and intensive movement tasks, may still contribute to discomfort if not properly managed.

In conclusion, XR technologies, particularly AR and MR, show strong potential to enhance patient engagement and support personalized, multisensory therapeutic approaches that foster neuroplasticity and adherence to rehabilitation protocols.

Future Research and Application

Future research should analyze the synergistic effects of VR and AR interventions and their impacts on motor recovery and quality of life in clinical populations. Additionally, efforts to address the limitations of existing studies and promote standardized reporting practices will contribute to advancing the field of VR-based neurorehabilitation.

Emphasizing the practical implications for clinicians will help bridge the gap between research and application, ensuring that these innovations are used effectively in real-world settings. Future studies should focus on long-term outcomes associated with XR interventions, as well as their effects on various patient populations. The success of XR interventions may depend significantly on patient engagement and individual preferences.

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Data Availability

The authors declare that all data analyzed in this review are included in this article and its supplementary information.

Authors' Contributions

Conceptualization: MM, OC, CD, DM, PB
Data curation: MM, OC, MCI, FM
Formal analysis: MM, OC
Funding acquisition: DM
Investigation: MM, OC, CD
Methodology: GD, OC, MM
Project administration: MM, DM
Resources: MM, DM, OC
Software: GD, MCI
Supervision: FM, PB, DM
Validation: GD
Visualization: GD
Writing – original draft: OC, MM, CD
Writing – review & editing: MCI, OC, MM, CD

Conflicts of Interest

None declared.

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Multimedia Appendix 1
Relevant literature involving virtual, augmented, and mixed reality applications for motor neurorehabilitation focused on body representation.
[DOCX File, 73 KB - xr_v2i1e63487_app1.docx]

Checklist 1
PRISMA-ScR checklist
[DOCX File, 87 KB - xr_v2i1e63487_app2.docx]

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Abbreviations

AR: augmented reality
EEG: electroencephalography
EMG: electromyography
FBI: full-body illusion
FPP: first-person perspective
HMD: head-mounted display
KINVIS: kinesthetic perception illusion induced by visual stimulation
MR: mixed reality
MRI: magnetic resonance imaging
NOS: Newcastle-Ottawa Scale
PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews
SCI: spinal cord injury
TPP: third-person perspective
VR: virtual reality
XR: extended reality

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Virtual Humans in Virtual Reality Mental Health Research: Systematic Review

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Abstract

Background: Virtual reality (VR) is showing increasing promise for assessing, understanding, and treating mental health difficulties. Virtual humans (VHs) represent a key aspect within many VR mental health applications. While VHs can play diverse roles and display varied characteristics, their design and influence have rarely been the primary focus of mental health research.

Objective: We aimed to carry out a systematic review of how VHs in immersive VR have been used in applications for mental health, focusing on their roles and interaction types, and the human characteristics being tested.

Methods: Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, we searched PubMed, MEDLINE, PsycINFO, Scopus, and Web of Science, using defined keyword combinations involving VR, VHs, and mental health. Eligible studies included peer-reviewed research using immersive VR with VHs in a mental health context, without restrictions on study design or population. We excluded nonimmersive VR, nonmental health applications, and papers without empirical data. Data were synthesized narratively, and a taxonomy to categorize VHs that we developed was used.

Results: A total of 79 studies met all eligibility criteria. VHs were most frequently applied in studies on social anxiety (n=18), eating disorders (n=18), and psychosis (n=15). They were primarily used as active social interaction partners (n=40), as part of virtual crowds (n=16), and as virtual bodies for participants (n=23). Explicit interactions dominated active partner studies, while implicit and passive or no interactions were prevalent in crowd and body studies. Over half of the studies (n=44) varied the VH characteristics, with body size and gender being the most common variables, and personality was explored in fewer studies (n=5). Only a limited number of studies provided detailed descriptions of VH appearance and behavior, with some including still images and videos.

Conclusions: VHs are versatile tools to be used within VR mental health applications, but their design features are inconsistently reported and insufficiently examined in relation to intervention outcomes. Evidence is limited by heterogeneity in study aims, designs, and populations, and by incomplete reporting of VH characteristics, which constrains replication and cross-study comparison. Standardized reporting and systematic investigations of VH design are needed to optimize their roles in evidence-based mental health applications.

Trial Registration: PROSPERO CRD42021244748; https://www.crd.york.ac.uk/PROSPERO/view/CRD42021244748

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KEYWORDS
virtual reality; virtual human; agent; avatar; mental health

Introduction

Virtual humans (VHs) have been part of virtual reality (VR) mental health applications since the late 1990s. The pioneering work by Riva and Melis [1] used images of a female silhouette in VR to represent the participant's body, marking one of the earliest uses of VHs in mental health research. Other early studies showed that virtual audiences could effectively induce anxiety in participants [2,3]. Since approximately 2013, advancements in VR technology and reductions in cost have significantly improved accessibility, enabling the use of VHs in research areas such as understanding paranoia [4,5], managing autism-centered interventions [6,7], and improving symptoms from posttraumatic stress disorder (PTSD) [8]. Some recent applications have integrated virtual coaches to guide patients and automate treatments [9,10], as well as body swapping

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experiences that allow participants to switch between different entities to experience perspective changes [11-13].

VHs enable researchers to simulate social interactions commonly encountered in daily life [14,15] or under special circumstances such as conflict or danger [16,17]. They can also serve as the self-representations of participants through the sense of embodiment and the creation of the illusion that the virtual body they see and control is their own body [18]. Compared to experimental setups with trained real actors, VHs provide greater experimental control and repeatability, preserving ecological validity [19].

Despite their growing use and potential, VHs have not been studied thoroughly in mental health research. This gap is partly due to the inherently multidisciplinary nature of the field, which requires expertise in psychology, immersive technologies, and 3D design to build VHs that are clinically suitable and technically feasible. Furthermore, conducting full-scale clinical trials to evaluate VH design within patient populations is often impractical. In contrast, the computer science community has explored VHs to optimize their visual and animation quality [20-22], develop realistic and adaptive behaviors [23-25], and create open-source character libraries [26-28]. These technical advances offer promising opportunities to extend the applications of VHs in mental health beyond their current use.

Understanding the role and impact of VHs in mental health research is essential for optimizing current implementations and discovering future applications. As VR and character creation software tools improve, VHs have the potential to play an even more important role in mental health, offering customized therapeutic experiences with fine-tuned emotional attributes designed specifically for each patient. We present a systematic review of research studies in mental health VR featuring VHs, from the early development of VR until November 2024. This review proposes a taxonomy based on the most important aspects to consider in VHs for mental health applications and classifies the studies found in this domain. The systematic review addresses the following questions:

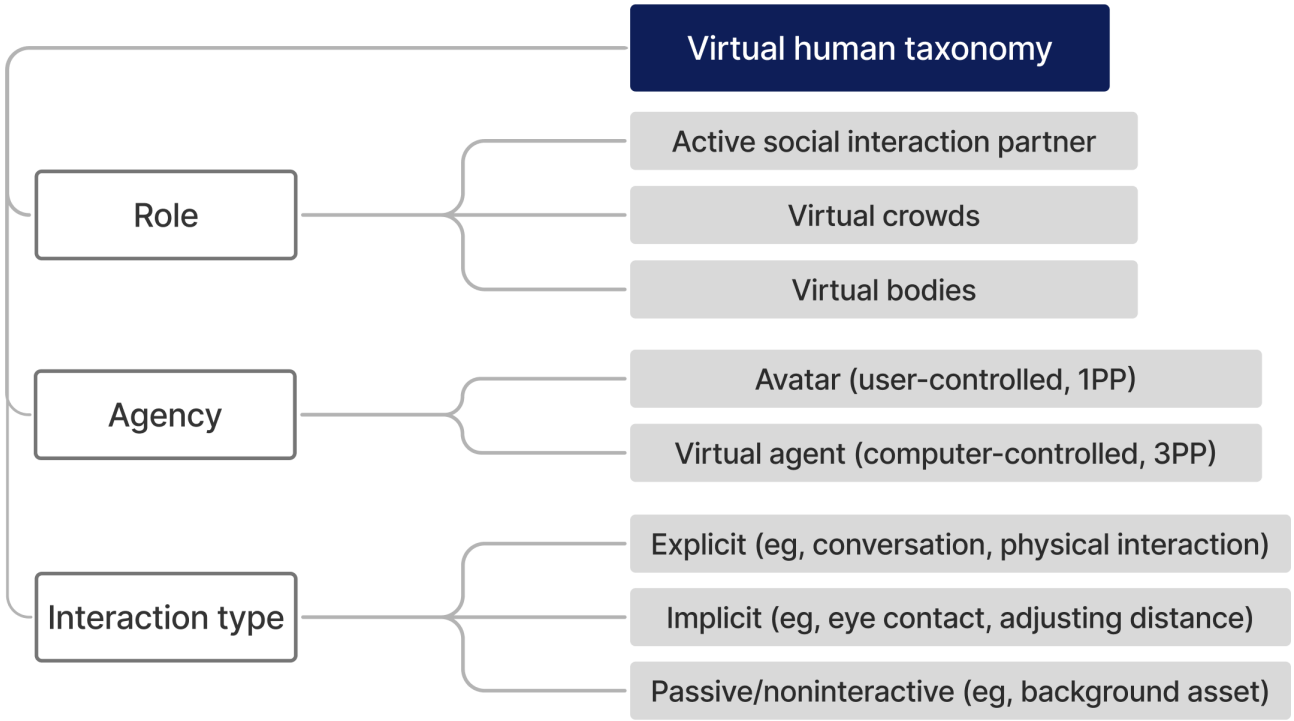
- What roles and functions have VHs played in VR mental health research?
- What have been the chosen agencies for VHs in VR mental health research?
- What characteristics of VHs have been examined in VR mental health research?

Methods

Categorizing VHs in Mental Health VR

We present a taxonomy of VHs in mental health VR (Figure 1), with categorization of their features into 3 main aspects: role, agency, and interaction type. These features were selected because they represent the critical dimensions influencing how VHs are designed, implemented, and experienced in mental health VR. Role defines the primary function of the VH within the virtual environment, agency determines the level of control and autonomy the VH exhibits, and interaction type describes the nature and depth of engagement between the VH and the participant. Together, these features provide a framework for understanding the diverse ways VHs are used in mental health research, enabling researchers to systematically evaluate their design and impact.

Figure 1. A taxonomy of virtual humans based on existing mental health virtual reality studies. 1PP: first-person perspective; 3PP: third-person perspective.



This framework was inductively derived from the included studies, and it was also supported by prior classification approaches in VR and virtual character research. Existing taxonomies highlight comparable dimensions—distinguishing

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characters according to their functional role [29,30], level of autonomy or agency [19,29,31,32], and communicative capacity or interaction features [19,30]. By aligning with these established design variables while adapting them to the specific context of mental health VR, our taxonomy provides both empirical grounding and theoretical consistency with prior frameworks.

Role

The role of VHs can be divided into 3 categories: active social interaction partners, virtual crowds, and virtual bodies. These categories were chosen to reflect the distinct ways VHs are used in VR mental health research across diverse applications. They emerged from recurring functional patterns observed across studies and align with prior literature around VHs, which supports the distinction among interactive agents, crowds, and avatars as the most common roles [33-35]. For example, Kyrlitsias and Michael-Grigoriou [33] differentiated VHs by their interaction scenario and level of engagement, while other researchers have examined the psychological impacts of virtual crowds compared to individual characters [34,36].

Active social interaction partners engage with participants to simulate interactions through verbal and nonverbal communication [13,37]. A virtual coach is an example of an active interaction partner that focuses on providing guidance or feedback to facilitate psychological treatment [9]. Virtual crowds, unlike active social interaction partners, have limited contact with participants or normally interact passively with implicit interaction, such as making eye contact [38]. It is common for virtual crowds to be part of the stimuli in the virtual world [39]. Virtual bodies focus on body representation, either by depicting a range of body types [1] or serving as the user's avatar for embodiment experiences [40].

Agency Avatars and Agents

Agency refers to the state or entity of taking action or exerting control [41] and can be categorized as avatars and virtual agents (VAs).

An avatar is a digital representation controlled by a user, serving as their own body in a different medium, for example, in a virtual environment [41]. Typically viewed from a first-person perspective, avatars are co-located with the user's real body. The real body is usually concealed, thus overriding them and creating the illusion that the body they see is their own body. The term "avatar" has often been misused in VR studies to describe any VH, even those who do not represent any user and are controlled by a computer.

A VA is a computer-generated character designed to simulate human interaction autonomously, moving and responding without being controlled by a real person [42]. VAs are mainly controlled by computers and typically viewed from a third-person perspective. They can exhibit varying degrees of autonomy, with semiautonomous agents combining computer automation with operator intervention. This approach is referred to as the Wizard of Oz technique [43] (a hidden operator simulates autonomous system behavior) and allows researchers to make VAs respond in real-time based on participant responses while still being computer-animated [19].

Interaction Types of VAs

VAs can have different degrees of interaction with human participants. We have categorized them into explicit, implicit, and passive or noninteractive.

Explicit interactions involve direct engagement between a VA and a participant, such as conversations, physical interactions (eg, shaking hands [44]), or collaborative activities (eg, playing a sport together [45]). Explicit interactions aim to replicate real-life social experiences, and they can be difficult to implement due to the complexity of managing a large pool of possible outcomes.

Implicit interactions include subtle behaviors, such as acknowledging the participant's presence by making eye contact or adjusting interpersonal distance, without fully engaging in an explicit interaction. Such interactions are less resource-intensive than explicit ones and still contribute to enhancing the sense of presence [46,47], making participants feel as if they are part of the scene rather than just being spectators.

Passive or noninteractive VAs act as background elements in VR environments, unresponsive to participant actions. They are easier to implement due to the scripted nature of their animations. They are used for crowd simulations and creating social situations such as populating a virtual restaurant [48] or constructing an office scene [49].

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria for eligible studies are summarized in Textbox 1. In brief, studies were required to (1) use VHs within an immersive VR setting; (2) involve assessment or intervention related to mental health conditions; and (3) include empirical data from human participants. Studies were excluded if they were not related to mental health, did not involve a VR-based VH, or were not available as peer-reviewed full-text articles in English.

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Textbox 1. Inclusion and exclusion criteria.

Inclusion criteria

- Population: Human participants
- Technology use: Immersive virtual reality (VR) with virtual human (VH) characters
- Application area: Mental health assessment or intervention
- Study type: Empirical study involving more than one participant with data collection
- Other criteria: English; available as full text

Exclusion criteria

- Population: Nonhuman studies
- Technology use: VR without VH or nonimmersive VR (eg, desktop system)
- Application area: Not related to mental health
- Study type: Reviews, protocols, abstracts only, commentaries, and opinion pieces
- Other criteria: Non-English; conference abstract

Search Strategy

The literature search was performed in PubMed, Scopus, MEDLINE (Ovid), PsycINFO (Ovid), and Web of Science (Clarivate), with title and abstract searches for keyword combinations involving (1) VR, (2) VH, and (3) mental health. The keyword query was structured as follows: [(virtual reality OR immersive virtual reality OR VR) AND (virtual human OR virtual character OR virtual agent OR avatar OR humanoid) AND ((assessment OR treatment OR therapy OR mental health) OR (mood disorders OR depress* OR bipolar OR mania OR paranoia OR psychosis OR psychotic OR schizophren* OR schizotyp* OR delus* OR hallucinat* OR phobias OR obsessive compulsive disorder OR OCD OR anxiety OR post traumatic stress disorder OR PTSD OR trauma OR anorexia nervosa OR bulimia nervosa OR eating disorders OR binge eating OR insomnia OR sleep OR nightmares OR circadian OR panic OR substance OR abuse OR cannabis OR tobacco OR alcohol OR amphetamine OR hallucinogens OR heroin))]. Details of the searches for each database in the corresponding platforms can be found in Multimedia Appendix 1. A completed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist [50] is presented in Checklist 1.

Article Screening

Following database searches, we identified 2596 records (Scopus, n=1232; Web of Science, n=712; PubMed, n=233; APA PsycINFO, n=247; MEDLINE, n=172) between 1997 and 2024 (final search: November 20, 2024). After removing 1085 duplicates (11 manually and 1074 via Covidence), 1511 unique records remained. Title and abstract screening excluded 1280 records that did not involve a VH character, did not use immersive VR, were unrelated to mental health, were nonhuman studies, or were non-English studies. The remaining 231 full-text articles were then assessed in detail, with the reasons for exclusion including the following: not immersive VR (n=73), not related to mental health (n=31), not full paper (eg, conference abstract) (n=21), no empirical data (n=19), no VH (n=11), and case study with only 1 participant (n=3).

Results

Search Results

Figure 2 (PRISMA diagram [50]) summarizes the search and screening results. In total, 79 studies were included in the review: 73 that met all eligibility criteria at full-text screening and 6 identified through citation chaining. We have provided a list of studies that primarily used VHs as active social interaction partners (Table 1), virtual crowds (Table 2), and virtual bodies (Table 3), along with a brief summary for each.

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Figure 2. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram. VR: virtual reality.

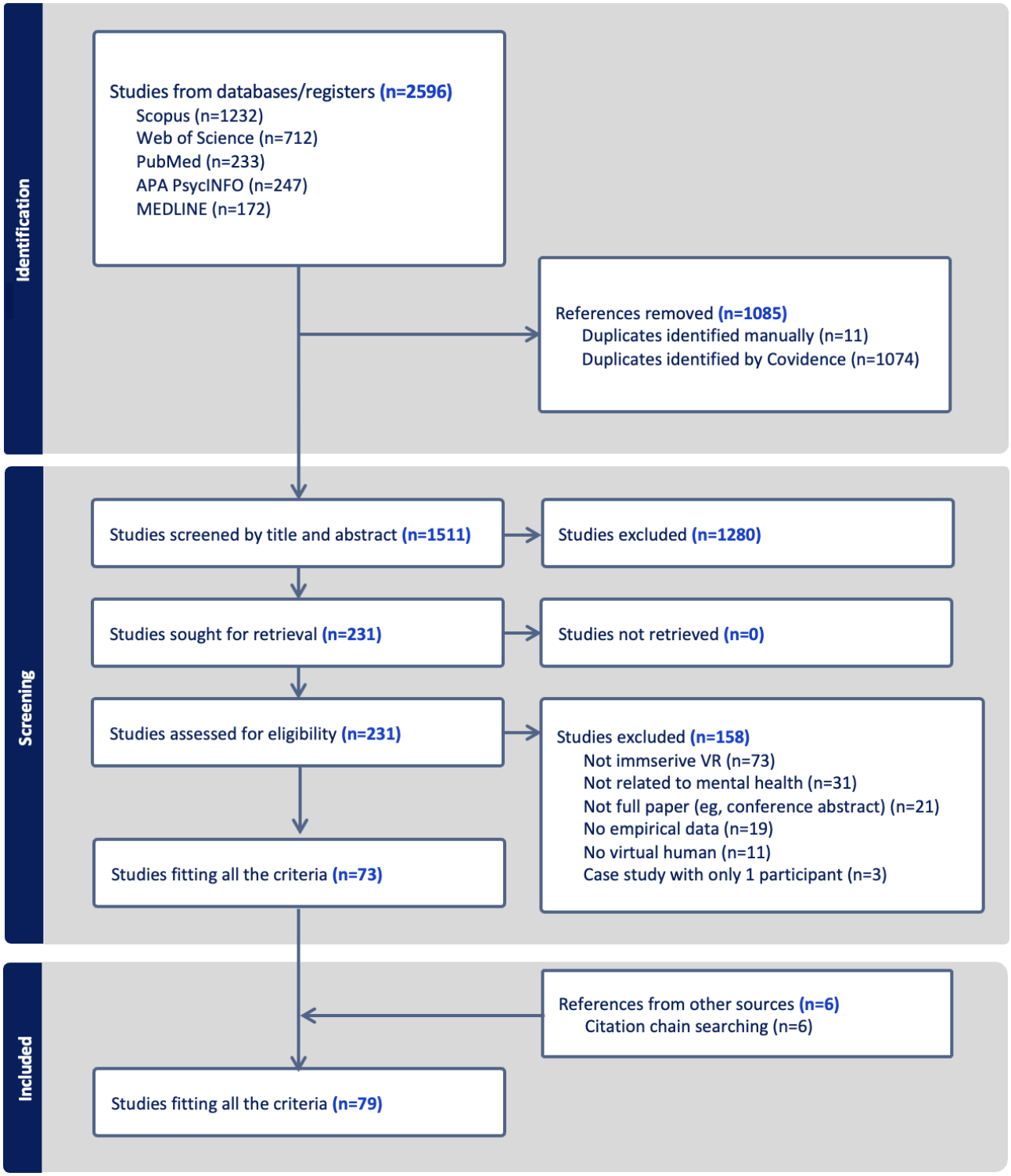

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Table . Studies that primarily used VHs[a] as active social interaction partners.

Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Lee et al [51], 2004	Active interaction partner	Agent	Implicit interaction	__[b]	Substance abuse	16	Males who smoked at least 10 cigarettes a day	VHs in cue exposure therapy exerted a stronger impact compared to seductive objects.
Park et al [52], 2009	Active interaction partner	Agent	Explicit interaction	Gender; Emotional facial expression	Psychosis	54	Patients diagnosed with schizophrenia and the nonclinical general population	VHs with emotional facial expressions successfully triggered emotional and biological responses.
Wieser et al [53], 2010	Active interaction partner	Agent	Implicit interaction	Gender; Gaze pattern; Interpersonal distance	Social anxiety	39	Females with social anxiety	Women paid more attention to the weight-gain areas on VHs than men.
Kwon et al [54], 2013	Active interaction partner	Agent	Explicit interaction	—	Social anxiety	20	Students with social anxiety	VHs provoked both stronger anxiety and presence than those in a nonimmersive display.
Powers et al [55], 2013	Active interaction partner	Semiautonomous agent	Explicit interaction	—	Social anxiety	26	Female undergraduates	Encountering VHs could trigger strong anxiety and fear.
Han et al [56], 2014	Active interaction partner	Agent	Explicit interaction	Attitude (positive, negative dialog)	Psychosis	45	Patients with schizophrenia and the nonclinical general population	Patients with schizophrenia had active avoidance of eye contact with VHs compared to healthy controls.
Hartanto et al [57], 2014	Active interaction partner	Semiautonomous agent	Explicit interaction	Attitude (positive, negative dialog)	Social anxiety	24	General population	Positive dialog feedback from VHs resulted in less anxiety, lower heart rate, and longer answers.
Pan et al [58], 2015	Active interaction partner	Semiautonomous agent	Explicit interaction	Personality (confident, shy)	Social anxiety	24	Male participants	VHs with a shy personality can be perceived as more friendly.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Fornells-Ambrojo et al [4], 2016	Active interaction partner	Semiautonomous agent	Explicit interaction	Responsiveness in social interaction	Psychosis	61	Male participants	Highly contingent VHs were perceived as more trustworthy for extremely paranoid individuals.
Ryan and Griffin [59], 2016	Active interaction partner	Agent	Implicit interaction	—	Social anxiety	27	Students	VR[c] exposure to a VH could successfully trigger social anxiety.
Falconer et al [11], 2016	Active interaction partner	Agent and/or avatar	Explicit interaction	—	Depression	15	Patients with depression	Changing the viewer perspective in a virtual social interaction could decrease self-criticism and increase self-compassion.
Robitaille et al [60], 2017	Active interaction partner	Agent and/or avatar	Explicit interaction	Responsiveness in social interaction	PTSD[d]	12	Nonclinical military members and military members with mild traumatic brain injury	Participants with PTSD displayed a lack of navigational behavior during a VH interaction.
Amaral et al [6], 2018	Active interaction partner	Agent	Implicit interaction	—	Autism	15	Patients with high-functioning ASD[e]	VH affected social attention among patients with autism.
Percie du Sert et al [61], 2018	Active interaction partner	Semiautonomous agent	Explicit interaction	—	Psychosis	15	Patients diagnosed with schizophrenia	VR therapy with VH could improve auditory verbal hallucinations and depressive symptoms.
Freeman et al [62], 2018	Active interaction partner (virtual coach)	Agent	Explicit interaction	—	Phobias	100	Individuals with a fear of heights	A virtual therapist could help automate the VR therapy.
Shin et al [63], 2018	Active interaction partner	Agent	Explicit interaction	Different levels of social pressure	Others	64	General population and patients with internet gaming disorder	Exposure to VHs in gaming cafes triggered gaming cravings.
Kothgassner et al [64], 2019	Active interaction partner	Agent and/or avatar	Explicit interaction	Perceived agency (avatar vs agent)	Social anxiety	56	Students	Virtual social support from a VH could be effective when the recipient thought it was from a human.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Quintana et al [65], 2019	Active interaction partner	Agent	Explicit interaction	—	Social anxiety	53	Female adults	Perception toward the VH could be affected by odorant manipulation.
Reichenberger et al [66], 2019	Active interaction partner	Agent	Explicit interaction	Gender; Interaction pattern (with or without aversive behavior)	Social anxiety	60	General population	VHs could be used to learn about social fear, and women reported higher fear compared to men.
Slater et al [13], 2019	Active interaction partner (virtual coach)	Agent and/or avatar	Explicit interaction	Dialog contents (self-dialog versus scripted dialog)	Depression	58	General population	Self-dialog VR coaching had better results than scripted VR counseling.
Seo et al [67], 2019	Active interaction partner	Agent	Explicit interaction	Interaction pattern (combination of gaze and pointing)	Social anxiety	33	General population	VHs with nonverbal behavior could be used to measure and promote joint attention.
Miloff et al [68], 2020	Active interaction partner (virtual coach)	Agent	Explicit interaction	—	Phobias	70	Patients with a fear of spiders	Alliance toward a virtual therapist is a significant predictor of treatment outcome in VR.
Nijman et al [69], 2020	Active interaction partner	Semiautonomous agent	Explicit interaction	Facial expression	Psychosis	22	Patients with psychotic disorders	VHs' facial expressions can be used to train participants' social cognition.
Kim et al [70], 2020	Active interaction partner	Agent	Explicit interaction	—	Others	36	Nonclinical male volunteers	VHs could be used for assessment and intervention to promote subjective well-being.
Lee et al [71], 2021	Active interaction partner	Agent and/or avatar	Explicit interaction	—	Psychosis	48	Patients diagnosed with schizophrenia and the nonclinical general population	The social context created by VHs impacted the difference in peripersonal space recognition.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Kothgassner et al [45], 2021	Active interaction partner	Agent and/or avatar	Explicit interaction	Perceived agency (avatar vs agent)	Social anxiety	84	Females	Social interaction experience with VHs was comparable to the real-life experience of cyberbullying.
Brander et al [72], 2021	Active interaction partner	Semiautonomous agent	Explicit interaction	Visual and behavioral traits of the virtual character through customization	Psychosis	109	Psychiatric hospital staff (psychotherapists, nursing staff, and administrators)	The function to customize VHs for VR treatment was highly valued by clinical staff.
Guldager et al [73], 2022	Active interaction partner	Agent	Explicit interaction	—	Substance abuse	372	Students aged 15 - 18 years	VR party simulation could improve adolescents' drinking refusal skills.
Freeman et al [9], 2022	Active interaction partner (virtual coach)	Agent	Explicit interaction	—	Psychosis	346	Patients with psychosis	Automated VR therapy with VHs could reduce anxious avoidance and distress in everyday situations.
Fusaro et al [7], 2023	Active interaction partner	Agent and/or avatar	Explicit interaction	—	Autism	53	General population and individuals with ASD	Autistic adults exhibited greater interpersonal distance with VHs.
Bektas et al [74], 2023	Active interaction partner	Agent	Explicit interaction	—	Eating disorder	70	Patients with anorexia nervosa	The addition of a VH to the virtual kitchen scene could increase the association between food-specific state disgust and symptoms of eating disorders.
Giguère et al [75], 2023	Active interaction partner	Semiautonomous agent	Explicit interaction	Voice and facial expressions	Substance abuse	19	Patients with cannabis use disorder and severe mental disorders	The VH intervention could reduce cannabis use among people with cannabis use disorder and severe mental disorders.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Halim et al [12], 2023	Active interaction partner	Agent and/or avatar	Explicit interaction	—	Depression	36	Young adults	Changing the viewer perspective through a virtual body swapping experience can help enhance self-compassion and reduce depressive symptoms.
Wei et al [37], 2023	Active interaction partner (virtual coach)	Agent	Explicit interaction	Head nods and facial expressions	Phobias	120	General population with a fear of heights	The detailed design of a virtual coach's emotional attributes could affect people's therapeutic alliance and their confidence in the VR therapy.
Artiran et al [76], 2024	Active interaction partner	Agent	Explicit interaction	Levels of attention (degrees of backchannels)	Autism	30	Patients with autism and the nonclinical population	The behavior of virtual interviewers influenced the gazes and head movements in individuals with autism.
Natali et al [77], 2024	Active interaction partner	Agent	Explicit interaction	—	Eating disorder	145	Patients with anorexia nervosa	VHs could provide positive social support to patients with anorexia nervosa in a VR food exposure scene.
Hidding et al [78], 2024	Active interaction partner	Agent	Explicit interaction	—	Others	68	Undergraduate students with high levels of self-criticism	Expressing compassion to a VH with similar self-criticism could reduce self-criticism and increase self-compassion.
Freeman et al [10], 2024	Active interaction partner (virtual coach)	Agent	Explicit interaction	—	Psychosis	11	Patients with nonaffective psychosis and low positive self-beliefs (aged 16 - 26 years)	Automated VR therapy with a virtual coach could improve self-beliefs and well-being in young patients with psychosis.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Yamashita and Yamamoto [79], 2024	Active interaction partner (virtual coach)	Agent and/or avatar	Explicit interaction	Identity of the VH (Freud or an intimate person of the participant)	Social anxiety	60	Students with personal problems	VR self-counseling with the intimate other avatar was most effective in improving people's anxiety.
Banakou et al [80], 2024	Active interaction partner	Agent	Explicit interaction	—	Social anxiety	45	General population with public speaking anxiety	Single-session VR exposure therapy with gradually increasing stimulus intensity may be as effective as multisession exposure for public speaking anxiety.

[a]VH: virtual human.

[b]Not applicable.

[c]VR: virtual reality.

[d]PTSD: posttraumatic stress disorder.

[e]ASD: autism spectrum disorder.

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Table . Studies that primarily used VHs[a] as virtual crowds.

Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Slater et al [3], 1999	Virtual crowds	Semiautonomous agent	Implicit interaction	Attentional focus level	Social anxiety	10	General population	A virtual audience could be used to treat public speaking fears; Higher perceived audience interest reduced public speaking anxiety.
Tarnanas et al [49], 2003	Virtual crowds	Agent	Passive interaction	__[b]	Social anxiety	120	General population and patients with work-related stress disorders	Virtual crowds triggered psychological and biological reactions in social anxiety.
Freeman et al [81], 2003	Virtual crowds	Agent	Passive interaction	—	Psychosis	24	General population	People tend to attribute their mental states to VHs.
Freeman et al [82], 2005	Virtual crowds	Agent	Passive interaction	—	Psychosis	30	People covering the whole range of paranoia	Neutral characters could elicit people's persecutory thoughts and be used to understand psychosis.
Freeman et al [15], 2008	Virtual crowds	Agent	Passive interaction	—	Psychosis	200	General population	Neutral characters could elicit paranoid ideation among the general population.
Cho et al [83], 2008	Virtual crowds	Agent	Implicit interaction	—	Substance abuse	10	Population with a low level of alcohol dependence	The presence of a VH in cue exposure induced stronger cravings.
Rizzo et al [39], 2010	Virtual crowds	Agent	Implicit interaction	—	PTSD[c]	20	Active duty service members	A VR[d] environment with VHs could simulate a war scene for the clinical treatment of PTSD and depression.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Brinkman et al [48], 2011	Virtual crowds	Agent	Passive interaction	Density; Ethnic appearance (White European or North African)	Social anxiety	26	General population and patients diagnosed with schizophrenia	VR exposure to an increased density and proportion of VHs with other ethnicities induced strong physiological arousal and distress.
Shiban et al [84], 2015	Virtual crowds	Agent	Passive interaction	—	Social anxiety	40	General population	VHs can be used to understand social fears in VR.
Mountford et al [85], 2016	Virtual crowds	Agent	Passive interaction	—	Eating disorder	18	General population	The exposure to VHs did not necessarily change people's in-state body image.
Atherton et al [86], 2016	Virtual crowds	Agent	Passive interaction	—	Psychosis	26	Males reporting paranoid ideation within the past month	People's own self-confidence could affect their paranoid thoughts toward the VHs.
Gürerk et al [14], 2019	Virtual crowds	Agent	Passive interaction	Different working behaviors	Social anxiety	108	General population	VHs with better working performance could motivate people to perform better.
Takac et al [87], 2019	Virtual crowds	Agent	Implicit interaction	Crowd size; Attentional focus level	Social anxiety	19	General population	Virtual audiences could elicit public speaking distress, which could last beyond VR sessions.
Wei et al [88], 2024	Virtual crowds	Agent	Implicit interaction	Facial expressions	Psychosis	122	General population with elevated paranoia	The detailed design of VH faces affected people's paranoid interpretations.
Gayer-Anderson et al [89], 2025	Virtual crowds	Agent	Implicit interaction	—	Psychosis	481	Adolescents	VR school scenes with VHs could help understand the precursors of adolescents' paranoid ideation.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Rovira et al [90], 2024	Virtual crowds	Agent	Explicit interaction	—	Substance abuse	100	People who smoke daily	VR exposure to smoking-cue VHs elicited stronger cigarette cravings than a neutral environment without VHs.

[a]VH: virtual human.

[b]Not applicable.

[c]PTSD: posttraumatic stress disorder.

[d]VR: virtual reality.

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Table . Studies that primarily used VHs[a] as virtual bodies.

Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Riva and Melis [1], 1997	Virtual body	Agent	Passive interaction	Body size	Eating disorder	119	General population	Virtual figures could be used to understand people's body images.
Perpiñá et al [91], 1999	Virtual body	Agent	Passive interaction	Body size	Eating disorder	13	Patients with eating disorders	VR[b] body image treatment could have a stronger impact than standard treatment.
Aymerich-Franch et al [92], 2014	Virtual body	Avatar	Passive interaction	Different levels of visual similarity to the participant	Social anxiety	187	General population	Having an avatar with an insimilar face could reduce anxiety.
Ferrer-Garcia et al [40], 2017	Virtual body	Agent	Passive interaction	Body size	Eating disorder	23	College students	Owning a fatter virtual body triggered higher levels of body anxiety and fears of weight gain.
Ferrer-Garcia et al [93], 2018	Virtual body	Agent	Passive interaction	Body size	Eating disorder	40	Female students	Owning a virtual body with different body sizes produced changes in body dissatisfaction.
Porras-Garcia et al [94], 2018	Virtual body	Agent	Passive interaction	Body size	Eating disorder	35	College students	Owning a larger-size virtual body increased people's body checking behaviors.
Porras-Garcia et al [95], 2019	Virtual body	Agent	Passive interaction	Body size	Eating disorder	85	College students	Women paid more attention to the weight-gain areas on the virtual figure than men.
Porras-Garcia et al [96], 2019	Virtual body	Agent	Passive interaction	Body size	Eating disorder	50	Undergraduates	Participants embodied through a synchronous visuotactile technique had higher anxiety-associated body dissatisfaction.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Mertens et al [97], 2019	Virtual body	Agent	Passive interaction	__[c]	Phobias	48	General population and individuals with a fear of spiders	Embodying participants into a virtual body from the 1PP[d] could improve the validity of fear conditioning.
Provenzano et al [98], 2020	Virtual body	Agent	Passive interaction	Body size	Eating disorder	20	Patients with eating disorders	Different perspectives (1PP vs 3PP[e]) of viewing the virtual body could change people's body image perception.
Scarpina et al [99], 2019	Virtual body	Agent	Passive interaction	Body size	Eating disorder	30	General population and participants with obesity	A body ownership illusion could be created for both people with obesity and the general population.
Spanlang et al [100], 2018	Virtual body	Agent	Passive interaction	Interaction pattern	Psychosis	27	General population	The body ownership illusion could trigger people's biological reactions.
Fisher et al [18], 2020	Virtual body	Agent	Passive interaction	Body size	Eating disorder	31	Female adolescents	Body size evaluation results from VR were comparable to paper-based measurements.
Porras-Garcia et al [101], 2020	Virtual body	Agent	Passive interaction	Body size	Eating disorder	41	Female college students	People could have an attentional bias toward the embodied virtual figure because of their own body dissatisfaction.
Gorisse et al [102], 2021	Virtual body	Agent and/or avatar	Explicit interaction	Interaction pattern (engagement level with virtual crowds)	Psychosis	30	General population	Observing a body double successfully engage in a VR social interaction could reduce paranoia.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Wolf et al [103], 2021	Virtual body	Agent and/or avatar	Passive interaction	—	Eating disorder	56	Females with normal weight	Embodiment through a VH could affect people's self-evaluation of their body weight.
van Gelder et al [104], 2022	Virtual body	Agent and/or avatar	Explicit interaction	Age (current self and future self)	Others	24	Convicted male offenders	Offenders' interactions with a VH representing their future self could reduce their self-defeating behaviors.
Yamamoto and Nakao [105], 2022	Virtual body	Agent	Passive interaction	Color	Depersonalization	31	Males with various depersonalization tendencies	People with depersonalization had weaker body ownership of the self-representative figure.
Burin et al [106], 2022	Virtual body	Agent and/or avatar	Passive interaction	Embodiment perspectives (1PP or 3PP)	Others	52	General population	Experiencing a moving virtual body from the 1PP could enhance stress coping ability.
Vahle and Tomasik [107], 2022	Virtual body	Avatar	—	Age (age-congruent and age-incongruent with the participants)	Others	74	General population aged between 18 and 30 years	The embodiment of an older avatar increased young adults' social motivation.
Mendoza-Medialdea et al [108], 2023	Virtual body	Avatar	—	Body size	Eating disorder	57	College women	Manipulating the VH body size could produce changes in body dissatisfaction.
Ascione et al [109], 2023	Virtual body	Avatar	—	—	Eating disorder	23	Adolescent patients with anorexia nervosa	The VR body attentional bias modification task could reduce body-related attentional bias among people with anorexia nervosa.

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Study	Role	Agency	Virtual agent interaction type	Parameters for manipulation	Condition	Participants, n	Participant characteristics	Comments on findings
Schroeder et al [110], 2023	Virtual body	Avatar	—	Body size	Eating disorder	43	Women with high or low body dissatisfaction	People with low body dissatisfaction showed stronger disembodiment during self-avatar mirror exposure.

[a]VH: virtual human.

[b]VR: virtual reality.

[c]Not applicable.

[d]1PP: first-person perspective.

[e]3PP: third-person perspective.

Mental Health Conditions

VHs were used in the following research areas in mental health: social anxiety (n=20), eating disorders (n=18), psychosis (n=17), substance abuse (n=5), phobias (n=4), depression (n=3), autism (n=3), PTSD (n=2), dissociative disorders (n=1), and others without specific mental health conditions (n=6).

Roles of VHs

We categorized the studies based on our taxonomy. Studies with overlapping roles were assigned to their primary role or the one with the highest interactivity. The roles of VHs in the included studies could be categorized into active social interaction partners (n=40), virtual crowds (n=16), and virtual bodies (n=23).

Active Social Interaction Partners

In 40 studies, VHs primarily served as active social interaction partners, tested in three different ways: (1) manipulating specific VH characteristics to assess their influence, (2) comparing the responses of clinical and nonclinical individuals, and (3) validating whether VHs in VR could trigger participants' responses or replicate the effects of real-world experiences.

Manipulating VH Characteristics

Twelve studies explicitly examined VH characteristics in social interactions. Wieser et al [53] investigated the anxiety-inducing effects of VH gender and gaze behaviors, finding that male agents with direct gaze elicited stronger anxiety and heart rate elevation among socially anxious women compared to female agents. A similar gender-related effect was observed in a VR fear conditioning program by Reichenberger et al [66], where female patients reported higher anxiety to aversive behaviors (eg, unpleasant air blasts) from male VAs than from female VAs. Park et al [52] and Nijman et al [69] focused on nonverbal behaviors, implementing different facial expressions on VHs to help individuals with psychotic disorders practice emotion recognition.

Researchers also manipulated the dialog responses (positive or negative) [57] and responsive frequency (high or low) [4] in conversation agents. Both the attitude and reply frequency of VHs in a conversation affected participants' behavioral (eg, interpersonal distance) and physiological (eg, heart rate) responses. In another study by Slater et al [13], participants engaged in a self-conversation by switching between 2 virtual bodies: first embodying a VH resembling themselves to describe their problem to a virtual Sigmund Freud and then embodying Freud to offer advice to their virtual self. This method resulted in a better perception of help compared to scripted dialog. A similar design was then adopted by Yamashita and Yamamoto [79], who found that VR self-counseling with an intimate other avatar was most effective in reducing anxiety. Furthermore, Pan et al [58] explored the impact of VH personality traits (confident vs shy) on participants' perceptions, showing that the shy VH was perceived as more positive and friendly. The effects of VH emotional attributes were further demonstrated by Wei et al [37], who showed that a virtual coach with positive facial expressions and affirmative nods enhanced participants' therapeutic alliance and treatment confidence during a VR fear-of-heights consultation. Lastly, the perceived agency of VHs was studied by Kothgassner et al [45,64], who compared participants' reactions when they believed they were interacting with a human versus a computer. Both experiments indicated that interactions with VHs can be as effective as interactions with real-life counterparts, provided participants believe the VH is controlled by a human in real time.

Comparing Clinical and Nonclinical Populations

In another use case, 5 studies used active interaction partners to assess the differences between clinical and nonclinical populations. Han et al [56] found that patients with schizophrenia avoided eye contact more often when interacting with 2 VHs in a 3-person conversation. Lee et al [71] used a ball game to study self-disturbances (eg, a distorted perception of one's own body boundary), suggesting that patients with schizophrenia showed longer reaction times and a weaker sense of body boundary compared to controls. Robitaille et al [60] designed a scenario to detect executive functioning difficulties in military personnel with traumatic brain injury. In a military patrol scene, a virtual male dressed as a civilian was used to simulate a divided attention task by approaching the participant. Both groups tolerated the experience, but those with posttraumatic brain injury displayed navigation difficulties after a divided attention task was added. Lastly, Fusaro et al [7] and

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Artiran et al [76] studied the differences in responses to VHs between participants with autism and nonclinical controls, and found that individuals with autism maintained greater interpersonal distance and responded less to VHs' social cues (eg, head turning and direct gaze) during virtual interviews.

Validation Studies With VHs

Twenty-two studies used active interaction partners to understand whether VHs in VR could trigger participants' responses or replicate the effects of a real-world experience. Ten studies involved participants with mental health conditions or specific phobias. Three of them were related to psychosis. Percie du Sert et al [61] tested a therapy for auditory verbal hallucinations in psychosis. Patients interacted with a VH representing the harmful voice they heard, and this exposure reduced their auditory verbal hallucination–related depressive symptoms. Freeman et al [9] developed gameChange, an automated VR therapy designed to address agoraphobia in psychosis. Patients were guided by a virtual coach through everyday scenarios like visiting a general practitioner or shopping, resulting in significant anxiety reduction, particularly in those with severe symptoms. More recently, Freeman et al [10] launched Phoenix, where a coach named Farah helps young patients with psychosis build self-confidence through guided tasks. Two other studies focused on eating disorders. Bektas et al [74] used a virtual kitchen scene in patients with anorexia nervosa, finding that a VH encouraging patients to challenge their disorder elicited stronger disgust reactions toward food. Natali et al [77] used the same scenario to induce positive mood, showing that supportive VHs can reduce anxiety and improve mood in patients with anorexia. Regarding phobias, Freeman et al [62] conducted a clinical trial for treating fear of heights. A VR coach called Nic guided participants through the different stages of the experience, leading to a significant reduction in their fear. Similarly, Miloff et al [68] used a holographic coach for spider phobia, where positive relationships predicted better outcomes. Falconer et al [11] promoted self-compassion in depression through role-swapping between a compassionate adult and a virtual child. Amaral et al [6] conducted a clinical trial using VHs for social and cognitive training in individuals with autism. A further study [75] applied VR to treat addiction to cannabis. Participants interacted with a VH representing a key figure in their cannabis consumption, such as a friend, a drug dealer, or those triggering their cravings, showing potential to reduce usage.

Among the remaining 13 validation studies involving nonclinical populations, 6 focused on social anxiety. Kwon et al [54] compared the effects of displaying VHs on a desktop monitor versus an immersive VR system, finding that immersive VR elicited stronger anxiety. This was further supported by a VR self-compassion induction [59] and a joint attention study [67], both of which concluded that VR had a greater capacity to induce anxiety compared to nonimmersive setups. Powers et al [55] examined participants' fear levels during VR and real-life interactions, noting that VR interactions triggered fear and anxiety similar to real-life situations. Banakou et al [80] suggested that single-session VR exposure could match multisession efficacy for public speaking anxiety. Moreover, Quintana et al [65] investigated the effects of smells on the perceptions of VHs. They discovered that exposure to fear-related odorants increased anxiety and reduced trust toward the virtual character. Other applications included improving depression via compassion practice [12], testing a customizable VH-based auditory hallucination therapy tool with hospital staff [72], and simulating alcohol refusal scenarios with VHs in VR FestLab [73]. Similar refusal training targeted gaming addiction [63] and nicotine addiction [51]. Finally, VR was used to promote well-being and self-confidence in youth by fostering strength awareness [70] and reducing self-criticism [78] through structured conversations with virtual characters.

Virtual Crowds

Sixteen studies used virtual crowds. Six of them were related to anxiety. In 1 of the earliest studies, Slater et al [3] compared public speaking to an attentive versus a disruptive virtual audience, finding that crowds could evoke anxiety comparable to real life, with better performance when the audience was attentive. Similar findings were reported by Takac et al [87], who suggested that the distress created in a virtual public speaking scenario could have lingering effects after the VR session. Virtual crowds were also used to populate a virtual office, finding that watching other VHs working was effective in triggering work-related stress [49] or creating peer effects to make people work more efficiently [14]. Brinkman et al [48] explored the effect of the size and ethnicity of virtual crowds in a bar scene, showing that VR exposure to an increased density and proportion of VHs with other ethnicities could induce stronger distress. Additionally, Shiban et al [84] incorporated air blasts and the sound of a female character screaming when participants approached a virtual crowd to study how individuals develop social fears and how these fears can be diminished or overcome through repeated exposure.

Six studies used a virtual crowd for research on psychosis. Early tests examined people's appraisals of neutral characters in a library scene, demonstrating that virtual crowds elicited persecutory thoughts for insights into psychosis [81,82]. Later research employed daily VR scenarios populated with VHs, such as in an underground train or school canteen, to understand factors associated with paranoid thinking. The findings suggested that paranoia could be predicted by anxiety, worry, perceptual anomalies, and cognitive inflexibility [15], and was influenced by individuals' self-confidence [86]. For adolescents, interpersonal threat or hostility heightened state paranoia [89]. Further, Wei et al [88,111] found that VH facial design influenced both paranoia and visual attention.

Mountford et al [85] used a virtual crowd in a virtual bus ride to study eating disorders. Participants were tested for their body image satisfaction, and the results showed that exposure to the virtual scenario with VHs did not necessarily change people's current feelings or perceptions about their body image. Cho et al [83] designed a VR bar to study alcohol cravings and found that the introduction of drinking characters led to a stronger drinking desire compared to simply displaying the alcohol in the scene. Similarly, Rovira et al [90] found that VR exposure to smoking-cue VHs elicited stronger cigarette cravings than neutral environments without VHs. Rizzo et al [39] used virtual

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soldiers and civilians for military training and found a reduction in PTSD severity in 80% of the study completers.

Virtual Bodies

VHs were used as body representations in 20 studies, with 15 focusing on eating disorders. Riva and Melis [1] conducted the first study in the literature on body image representation using VR. Participants selected virtual figures representing their current and ideal body size. Perpiñá et al [91] introduced a feature allowing patients with eating disorders to adjust the size of a virtual body to reflect their body image. Both showed VR's feasibility for assessing body image disturbances, with results comparable to paper-based measures but showing greater engagement [18]. While these early studies did not induce body ownership, later studies often aimed to do so.

Studies employing the body ownership illusion paradigm found that embodying a larger virtual figure led participants to check their virtual body more frequently [94,95] and experience a higher degree of self-dissatisfaction and anxiety [40,96,98,101,108]. In contrast, Schroeder et al [110] found that body dissatisfaction was not necessarily affected by the weight of the avatar, although people with higher body dissatisfaction exhibited more body-checking behaviors in weight-related areas.

Ferrer-Garcia et al [93] created a paradigm to reduce anxiety related to body image in female students by making them return to the normal-size virtual figure after experiencing a larger body. A similar method was used to alleviate body image distortion in both healthy-weight participants and those with obesity [99]. Wolf et al [103] compared the body weight perceptions of 2 groups of females: one that embodied a VH and another that observed the VH as another person's avatar. The self-embodiment group underestimated the body weight of the VH compared to those who rated the VH as another's avatar. Furthermore, Ascione et al [109] conducted a body-related attention bias modification task to reduce excessive visual focus on the weight-related areas of a self-represented VR body, which significantly decreased body dissatisfaction.

Three other studies used virtual bodies for psychosis research. Spanlang et al [100] examined whether self-fragmentation in VR, where participants embodied a VH while retaining physical presence in the real world, impacted the biological responses in patients with schizophrenia. Yamamoto and Nakao [105] found that perceiving a fake body as one's own reduced body ownership in depersonalization. Gorisse et al [102] used a virtual body double resembling each participant for a social VR task. They concluded that observing a body double engaging in VR social interactions could reduce persecutory thoughts during the task.

Additionally, van Gelder et al [104] demonstrated that alternating convicted offenders between their current and aged future selves reduced self-defeating behaviors. Similarly, embodying an older body could increase social motivation among young adults [107]. Besides, Burin et al [106] presented participants with a moving character from first-person and third-person perspectives. They concluded that a body illusion from the first-person perspective created stronger physiological activation to help people practice stress coping. Aymerich-Franch et al [92] assessed the impact of the facial similarity of a VH on participants, finding that embodying a figure with a dissimilar face reduced anxiety during VR presentations.

VAs and Avatars

Out of the 79 studies, 74 involved the use of VAs. Nine of them adopted a semiautonomous agent design, where facilitators manually triggered an audio effect [3,61], adjusted VH voices [75], or played prerecorded animations [4,55] to customize characters' behaviors in real time.

Regarding the interaction types of VAs, approximately half (39/74, 53%) engaged in explicit interactions with participants, primarily serving as active interaction partners. In 10 studies, VAs exhibited implicit interactions (eg, occasionally looking at participants and then looking away). Passive interactions were observed in 26 studies where VHs were used as virtual crowds and virtual bodies.

In the reviewed studies, the term "avatar" was often used to describe any type of VH, even when they did not represent the participant's self. Only 5 studies used VHs as participant avatars. For example, Aymerich-Franch et al [92] used an avatar with varying levels of visual similarity to the participant's face to study the self-embodiment experience. Additionally, 12 studies combined the use of agents and avatars to create perspective changes through body-swapping experiences in social interactions [11,13,104] or to explore the effects of vicarious agency (the perception of control over the VH) [102]. Kothgassner et al [45,64] further examined the effect of perceived agency by comparing participants' VR experiences with VAs and avatars. The results indicated that avatars could elicit stronger emotional responses compared to VAs.

Human Characteristics

Of the 79 studies reviewed, 44 examined the effects of manipulating specific characteristics of VHs. These manipulations aimed to assess how physical and behavioral attributes of VHs influence participants' perceptions and behavioral responses. The manipulated features included their visual appearance [48,52,99] (eg, gender, ethnicity, and body size), interaction behavior [7,76,87] (eg, interpersonal distance, eye gaze behavior patterns, and responsiveness toward participants), perceived agency [45,64] (VA or avatar), and emotions [52,75] (eg, emotional facial expressions) or personality [58]. While most of the traits were nonverbal behaviors, 4 studies explored the effects of verbal behaviors, including dialog content [13], conversation attitude (eg, positive vs neutral dialog) [56,57], and the voice of VHs [75]. The most frequently studied trait was body size (n=13), while traits, such as sense of affirmation [37] and personality [58], received limited investigation.

In addition to individual traits, 2 studies examined the effects of crowd size and density as independent variables in virtual crowd settings [48,87]. These studies explored how variations in the number and arrangement of virtual characters influence participants' sense of presence and anxiety in crowded environments.

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Discussion

Summary of Findings

This paper reviewed VR studies that included VHs in scenarios to understand and treat mental health difficulties. We examined 79 studies and categorized them based on the primary role of the VHs: active social interaction partners, virtual crowds, and virtual bodies. We focused on the use of agency, types of interactions, and characteristics of the VHs. VHs have served diverse purposes and demonstrated the ability to create psychological, behavioral, and physiological influences. However, few studies have provided comprehensive descriptions of VHs' visual appearance or behavioral capabilities. Without such details, it becomes challenging to assess their actual impact, and replicability is reduced. The potential of each VH role requires further exploration to address these gaps and the associated challenges.

Active Social Interaction Partners

Active social interaction partners interact explicitly with participants. A persistent challenge in this context has been enhancing the realism and responsiveness of these interactions, particularly during close-up engagements [19,112,113]. Improving both visual fidelity and behavioral plausibility is essential for achieving lifelike interactions [30,114,115]. Consistent design of both visual and behavioral elements is needed to avoid the uncanny valley, where characters appear almost human but evoke discomfort due to subtle imperfections, as also seen in VR interactions [116,117]. Additionally, it is important to consider VH behavioral plausibility and consistency across multiple behavioral channels, including both verbal and nonverbal communication (eg, body movement, facial expressions, voice, and dialog content). For example, Choudhary et al [118] demonstrated that mismatches between facial expressions and vocal tone (eg, a happy face with an unhappy voice) negatively impacted participants' immersion and engagement, highlighting the importance of aligning these communication modes.

Regarding responsiveness and interactivity, current feedback in mental health VR often relies on prerecorded actions triggered by participant inputs, such as user interface selection, position, or response time [49,60,65]. Future applications could integrate machine learning algorithms, such as reinforcement learning, to create autonomous VHs that learn from experience [119]. These VHs could adjust parameters, such as the interpersonal distance, to maximize attention and keep participants engaged. Algorithms could detect interaction dynamics (eg, participant attitudes and responsiveness) and adjust VH behaviors in real-time to achieve specific therapeutic goals, particularly in applications encouraging positive behaviors. Another area to explore is the real-time monitoring of physiological responses to create adaptive interactions based on participants' affective state. A few of the studies reviewed used biometric data (eg, salivary alpha-amylase, heart rate, and galvanic skin) to evaluate physiological responses [52,100,106], but none leveraged these data to enhance interaction fidelity. Real-time estimates of emotional arousal and valence could enable VHs to respond meaningfully to participants' emotional changes [120].

A virtual coach represents a specific type of active social interaction partner, designed to guide and motivate users toward positive behavioral changes while facilitating the automation of therapy delivery. Focus group feedback indicated that users valued the convenience, accessibility, and anonymity provided by a virtual coach, but they also expressed concerns about the coach feeling unrelatable and difficult to engage with [121]. The development of a VR coach should incorporate knowledge and feedback from domain experts and targeted user groups to ensure it is tailored to the specific age range and mental health conditions it aims to address [122,123]. Generally, increasing the engagement and friendliness of communication from virtual coaches is likely to improve their effectiveness and the outcomes of VR therapy [68].

Virtual Crowds

In virtual crowd studies, it is standard practice to use identical designs and behaviors for characters that share common objectives to achieve a balance between realism and computational efficiency [124,125]. However, visual and behavioral repetition patterns in a group of VHs are very noticeable and decrease fidelity. Introducing variations in appearance and movement is important to diversify crowds and avoid these patterns [126,127]. Visual diversity can be achieved, for example, by randomizing height, body shape, hair color, and clothing. Behavioral diversity can be enhanced by blending animations, using motion capture data from multiple individuals, and implementing procedural animations with a certain degree of randomization to generate varied movements in real-time based on environmental and interaction dynamics.

There are additional considerations. When virtual crowds have autonomy to move around a space, each one should navigate naturally, avoiding collisions with static and dynamic obstacles. For example, Trivedi and Mousas [128] implemented a crowd behavior system for a VR street scene, where each VA had navigation scripts with steering and pathfinding capabilities to avoid collisions. Each agent also had a customizable target location, walking speed, and animation (eg, head direction and gaze pattern). Other advanced virtual crowd control systems generate real-time behaviors driven by user input and the dynamics of other virtual entities within the crowd [129]. These designs could be applied in mental health applications to improve crowd interactions and better understand responses to busy environments.

Virtual Bodies

Studies involving virtual bodies predominantly helped individuals reassess their body image biases or gain new perspectives, provided by the body ownership illusion. These use cases require improved methods to enable the sense of embodiment. Existing methods like visual-motor synchrony [97] and visual-tactile synchrony [96,99] are designed to align visual feedback with participants' movements or tactile sensations to enhance the illusion of ownership over the virtual body. While effective in initiating this illusion, sustaining or manipulating it throughout the VR experience remains challenging. Mismatched sensory feedback or slight discrepancies in motion can disrupt the sense of embodiment [130,131]. Integrating other sensory modalities, such as auditory

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feedback (eg, footsteps and voice modulation) or olfactory feedback (eg, simulating a scent experience based on the participant's location), could enhance the body ownership illusion. Combined multisensory feedback has been shown to strengthen and prolong the influence on embodiment, affect, and behaviors [132,133].

Customizing virtual bodies to closely resemble participants can enhance the sense of embodiment. Aymerich-Franch et al [92] found that embodying a virtual body with a similar face increased self-association and anxiety during public speaking tasks compared to dissimilar faces. This provides evidence for the importance of avatar personalization and its potential to modulate emotional responses. Customization should consider not only physical appearance but also factors like ethnic background [134] and voice [135]. These factors can significantly contribute to the body ownership illusion.

Ethical Considerations and Recommendations

The integration of VHs in mental health VR raises potential ethical and methodological challenges. A key concern is the lack of standardization in the technical implementation of character creation and animation. Many implementations rely on proprietary or nonstandardized software, which complicates replication and cross-study comparison. When such tools become inaccessible or difficult to adopt, scaling the experiments or building cumulative evidence becomes challenging. Moving toward open-source platforms or developing shared technical standards would enhance reproducibility and research efficiency. Encouragingly, the computer science community has started to introduce open-source 3D character libraries [26-28], some of which have already been used in mental health research [11,13]. This provides early examples of community-driven resources that could serve as a foundation for broader standardization.

Equally important is the transparency of reporting with regard to VHs. Many current studies provide limited descriptions of VH characteristics, and some even omit a general description of VR scenes. Such omissions reduce study transparency and limit replicability for continuous research. General ethical guidelines from the UK National Institute for Health and Care Excellence (NICE) [136] emphasize clear reporting of system design and capabilities for therapeutic applications. The CONSORT-EHEALTH extension recommends that digital health interventions specify intervention components, delivery modes, tailoring, and technical features [137]. More specifically, RATE-XR (reporting for the early-phase clinical evaluation of applications using extended reality) provides a reporting framework for early-phase clinical extended reality applications, with a checklist covering application characteristics, hardware, software, and development details [138]. For more tailored standards, VH-specific reporting practices, ideally supported by visual and technical documentation (eg, screenshots, videos, and model specifications), are needed to improve reproducibility and comparability across disciplines.

Moreover, data privacy and participant safeguards also require careful consideration. VH-mediated applications can sometimes collect sensitive physiological, behavioral, and conversational data [13,48,139], raising risks related to identity inference and emotional profiling, where user behavior data can sometimes be used to infer sensitive personal traits [140]. In addition, embodiment-based interactions can sometimes provoke unintended psychological effects, such as distress or overidentification with the VH [141,142]. To mitigate these risks, researchers should implement robust informed consent procedures and ensure secure data handling. Safeguards, such as participant prescreening, clinician oversight, built-in safety controls (eg, pause or exit functions in VR software), and structured debriefing protocols, are essential to protect participants.

Limitations

This systematic review has several limitations. First, our search strategy may not have captured all relevant VR mental health studies involving VHs. We used 5 databases and conducted searches limited to titles and abstracts with fixed keyword combinations, excluding studies that did not simultaneously mention VR, VHs, and mental health. To maintain a consistent search strategy across platforms, we did not use controlled vocabulary, such as Medical Subject Headings (MeSH) in PubMed, which may have further reduced recall. To mitigate this, we conducted citation chaining and identified 6 additional eligible studies not captured in the original search. However, the omission may have still remained, and it may have narrowed the evidence base. Future updates should refine the search strategy by incorporating broader synonyms and controlled vocabulary, and including gray literature sources.

Second, there are limitations in our categorization of VH roles and characteristics. Existing taxonomies used to classify virtual characters and their behaviors [30,143] are at least a decade old and do not specifically focus on VR studies in mental health. We developed our own classification based on the usage of VHs in the reviewed studies. This framework is tailored to mental health research, and it may require adaptation for application in other research areas. Ongoing efforts to develop and validate updated, domain-general taxonomies would improve consistency and comparability across studies.

Third, most included studies were pilot, feasibility, or exploratory in nature, often with small sample sizes and limited follow-up. While we included only empirical studies with more than one participant to enhance rigor, the predominance of early-stage designs may have constrained overall study quality and generalizability. Future research could prioritize more robust designs, such as randomized controlled trials or longitudinal studies with quality assessments, to generate stronger and more interpretable evidence.

Fourth, regarding result analysis, we opted for a narrative review approach instead of a quantitative evaluation to measure the quality and effectiveness of VHs across studies. This choice was made due to the variability in study objectives (ranging from validation and assessment to clinical treatments) and the diversity in participant characteristics. In addition, many studies lacked sufficient descriptions of VH attributes and consistent reporting on VR systems and software, which constrained systematic comparison and aggregation. As the field progresses and reporting becomes more standardized, meta-analyses and formal quality appraisals will become feasible.

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Conclusions

VHs can be used in many different ways within immersive VR mental health research and have served primarily as active interaction partners, virtual crowds, and virtual bodies. Across the 79 studies reviewed, most VHs were computer-controlled agents, with perceived agency shaping emotional and behavioral responses. Research to date has predominantly examined body size and gender, with limited attention to emotional expression or personality traits. Many studies provided insufficient technical and visual details on VH design, limiting reproducibility and cross-study comparison. Addressing these gaps is crucial for advancing the evidence base and understanding how specific VH characteristics influence mental health outcomes in VR. To our knowledge, this review provides the first synthesis of the use of VHs in VR mental health, offering a potential foundation for future VR programming of VHs and future studies on their implementation.

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Authors' Contributions

Conceptualization: SW (lead), AR (equal), DF (equal)
Data curation: SW
Formal analysis: SW
Methodology: SW (lead), AR (supporting), DF (supporting)
Supervision: AR (equal), DF (equal)
Writing – original draft: SW
Writing – review & editing: SW (lead), AR (supporting), DF (supporting)

Conflicts of Interest

DF holds options in XRHealth, a virtual reality mental health treatment company. The other authors do not have any competing interests.

Multimedia Appendix 1
Search query details.
[DOCX File, 21 KB - xr_v2i1e75087_app1.docx]

Checklist 1
PRISMA checklist.
[DOCX File, 277 KB - xr_v2i1e75087_app2.docx]

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Abbreviations

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PTSD: posttraumatic stress disorder
VA: virtual agent
VH: virtual human
VR: virtual reality

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Virtual Reality Reminiscence Therapy in Dementia Care: Scoping Review of Research

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Abstract

Background: Dementia is a progressive neurological disorder affecting cognitive and social functioning, posing challenges for patients and caregivers. Traditional medications often have adverse effects, emphasizing the need for nonpharmacological options such as reminiscence therapy (RT). Virtual reality (VR) has emerged as a promising tool in dementia care, providing immersive experiences that stimulate memory, enhance emotional well-being, and reduce the behavioral and psychological symptoms of dementia.

Objective: This scoping review assesses the feasibility and implementation challenges of delivering RT via VR in dementia care. Specifically, it examines the types of VR systems used, their therapeutic benefits, and the barriers to their adoption.

Methods: We screened 5 electronic libraries: Google Scholar, ACM Digital Library, IEEE Xplore, MEDLINE, and PubMed. Studies published between 2000 and 2025 were included if they examined the use of VR for RT in people with dementia. Data were charted based on PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) guidelines and analyzed thematically for feasibility, VR system type, therapeutic effects, and implementation considerations.

Results: A total of 15 studies met the inclusion criteria. The findings indicate that VR is feasible and well-accepted among people with dementia, fostering high engagement with minimal adverse effects. Fully immersive VR systems, which use head-mounted displays, are the most frequently used, while semi-immersive alternatives with large screens provide a more cost-effective option. RT via VR has been shown to improve reminiscence, enhance mood, and encourage social interaction. However, its impact on cognitive function remains inconclusive. Significant barriers to implementation include high costs, limited availability of VR infrastructure in care, and the need for specialized caregiver training.

Conclusions: RT via VR presents a promising advancement in dementia care. Future research should focus on developing cost-effective, scalable VR solutions, designing personalized VR experiences tailored to individual needs, and creating structured training programs for caregivers. Longitudinal studies are necessary to determine the long-term therapeutic effects of VR compared to traditional RT.

(JMIR XR Spatial Comput 2025;2:e73539) doi:10.2196/73539

KEYWORDS

dementia; virtual reality; reminiscence therapy; nonpharmacological interventions; cognitive stimulation; emotional stimulation

Introduction

Background

Dementia is a progressive neurological disorder and an umbrella term for conditions that lead to the deterioration of cognitive and social functioning. It impacts various mental faculties, including memory, problem-solving, orientation, comprehension, calculation, learning capacity, language, and judgment [1]. People with dementia often experience behavioral and psychological symptoms of dementia (BPSD), including mood disturbances, aggression, irritability, apathy, and emotional dysregulation, which further reduce their quality of life and place significant burdens on caregivers [2,3].

Worldwide, dementia affects a rapidly growing population. Only in 2021, the World Health Organization estimated that over 55 million people were living with dementia, a number expected to rise to 82 million by 2030 and 139 million by 2050 [1]. It is currently the seventh leading cause of death worldwide and a major cause of disability and dependency among older adults [1]. This rising prevalence underscores the urgent need for interventions, as dementia imposes significant physical, psychological, social, and economic burdens [2].

While no cure exists, treatments aim to alleviate symptoms and improve the quality of life for people with dementia. Pharmacological treatments, such as neuroleptic or sedating medications, have historically been overused despite their

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association with adverse effects, including accelerated cognitive decline, cardiovascular issues, infections, and emotional distress [4,5]. Consequently, nonpharmacological interventions have gained prominence as preferred approaches for addressing dementia symptoms. Among these, reminiscence therapy (RT) has emerged as a particularly effective psychosocial intervention. RT involves structured recall and discussion of past experiences using prompts such as photographs, music, personal objects, and storytelling [6]. Evidence suggests that RT can improve mood, reduce agitation, and enhance social interaction in people with dementia [6,7].

The application of RT varies significantly across studies, with interventions delivered in both personalized and nonpersonalized formats. Some studies combined both approaches [8], while others focused exclusively on either personalized RT [9,10] or nonpersonalized RT [6,11]. RT methods, such as group storytelling, memory books, multisensory activities, and music therapy, have been widely used [9,12]. Meanwhile, digital RT, which integrates digital apps, video games, and web-based platforms, has introduced novel ways of engaging people with dementia [8,10,11]. Such digital interventions have shown promise in increasing engagement and reducing social isolation [12]. However, challenges such as cost, feasibility, and inconsistent therapeutic outcomes remain [6].

Emerging Role of Virtual Reality in RT

Recent technological advancements, particularly virtual reality (VR), have expanded the possibilities for nonpharmacological dementia care [13,14]. VR creates immersive, computer-generated environments that simulate real-world experiences, engaging users' senses through visual, auditory, tactile, and even olfactory stimuli [15]. These environments enable people with dementia to transcend physical limitations and explore familiar or calming settings, such as natural landscapes or culturally significant landmarks [14,16,17]. By simulating personalized environments, VR interventions have demonstrated the potential to reduce anxiety, depression, aggression, and social withdrawal while promoting cognitive engagement and emotional well-being [13,14,18-20].

Studies show that personalized VR experiences, tailored to an individual's preferences and abilities, have been linked to improved cognitive functions, such as memory recall and spatial navigation, as well as reductions in agitation and emotional dysregulation [21]. Moreover, VR-based interventions offer scalable, customizable solutions that can be adapted to the diverse needs of people with dementia while minimizing mobility challenges [14,18,22-25].

Despite these promising findings, questions remain regarding the feasibility and the limitations of integrating VR into RT for dementia care. While several systematic and scoping reviews have examined the use of virtual reality reminiscence therapy (VRRT) for older adults or people with cognitive impairments [26,27], none, to the best of our knowledge, have focused exclusively on people with dementia. Moreover, existing reviews often conflate diverse populations, such as cognitively healthy older adults, those with mild cognitive impairment, and individuals with dementia, limiting the specificity and relevance of their conclusions to people with dementia. Further on the above, these prior works also tend to overlook important dimensions such as the comparative use of semi-immersive virtual reality (SI-VR) versus fully immersive virtual reality (FI-VR) systems, the role of content personalization, and implementation barriers in real-world care. This review addresses these critical gaps by focusing solely on people with dementia and providing a comprehensive synthesis of empirical and experimental studies that evaluate both the therapeutic impact and practical challenges of VR-based RT. As VR technology continues to evolve, further research is needed to determine its optimal application, long-term effects, and best practices for integration in dementia care. This study examines the implementation of VR in RT for people with dementia residing in long-term care facilities, hospital environments, or community settings over the past 2 and a half decades (2000 - 2025). By synthesizing findings from empirical and experimental research, the review addresses critical research questions (RQs), including the following:

- RQ1. How feasible is integrating VR into RT for dementia care?
- RQ2. What are the outcomes of VRRT?
- RQ3. What limitations currently hinder the application of VR in RT?
- RQ4. What are the potential future directions for research and implementation of VR in RT?

Methods

Literature Review Strategy

The electronic databases Google Scholar, ACM Digital Library, IEEE Xplore, MEDLINE, and PubMed were searched in January 2025 using a combination of search terms designed to capture studies on the use of VR in RT for people with dementia. Three core concept clusters were applied: term A included "dementia," and term B included "reminiscence" OR "reminiscence therapy," and term C included "virtual reality." A filter was applied to include only studies that were published between 2000 to 2025. The reference lists of articles that met the eligibility criteria were further perused to identify additional studies that may fall within the scope of this review.

Inclusion and Exclusion Criteria

Studies eligible to be included in this review had to meet the following inclusion criteria: (1) human participants were involved, (2) the full article was written in English, and (3) papers studied VR used for RT in dementia. The exclusion criteria were (1) publications where the study of VR used for RT in dementia was not the primary aim of the study, (2) publications that were not original studies (ie, review articles, letters, medical hypotheses, etc), (3) publications that presented trials studying subjects with no dementia, (4) duplicate publications, (5) publications whose abstract was not accessible, and (6) publications whose full text could not be obtained.

Data Collection Process

Following the identification of eligible publications, all relevant data were collected using a structured coding scheme in an Excel (Microsoft Corp) file. The data collected included titles, sample size, type of dementia, instruments used, methodology, and

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findings. Additional fields specific to studies involving VR included the type of VR system (nonimmersive, semi-immersive, or fully immersive), VR content or intervention, feasibility, limitations, and future directions.

Data Synthesis and Analysis

This study used aggregated data where possible, per the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) guidelines (Checklist 1: PRISMA-ScR). Key domains extracted included feasibility, therapeutic outcomes (emotional, cognitive, and social), and implementation barriers, allowing for cross-study comparison and pattern identification.

Results

Search Results

This search strategy yielded the identification of 136 articles. Following the eligibility assessment, 121 articles were excluded. In total, 15 papers satisfied the inclusion criteria and were used for this review (Table 1). Figure 1 illustrates the study selection process.

Figure 1. Flowchart detailing the process used to identify and select the papers included in the analysis.

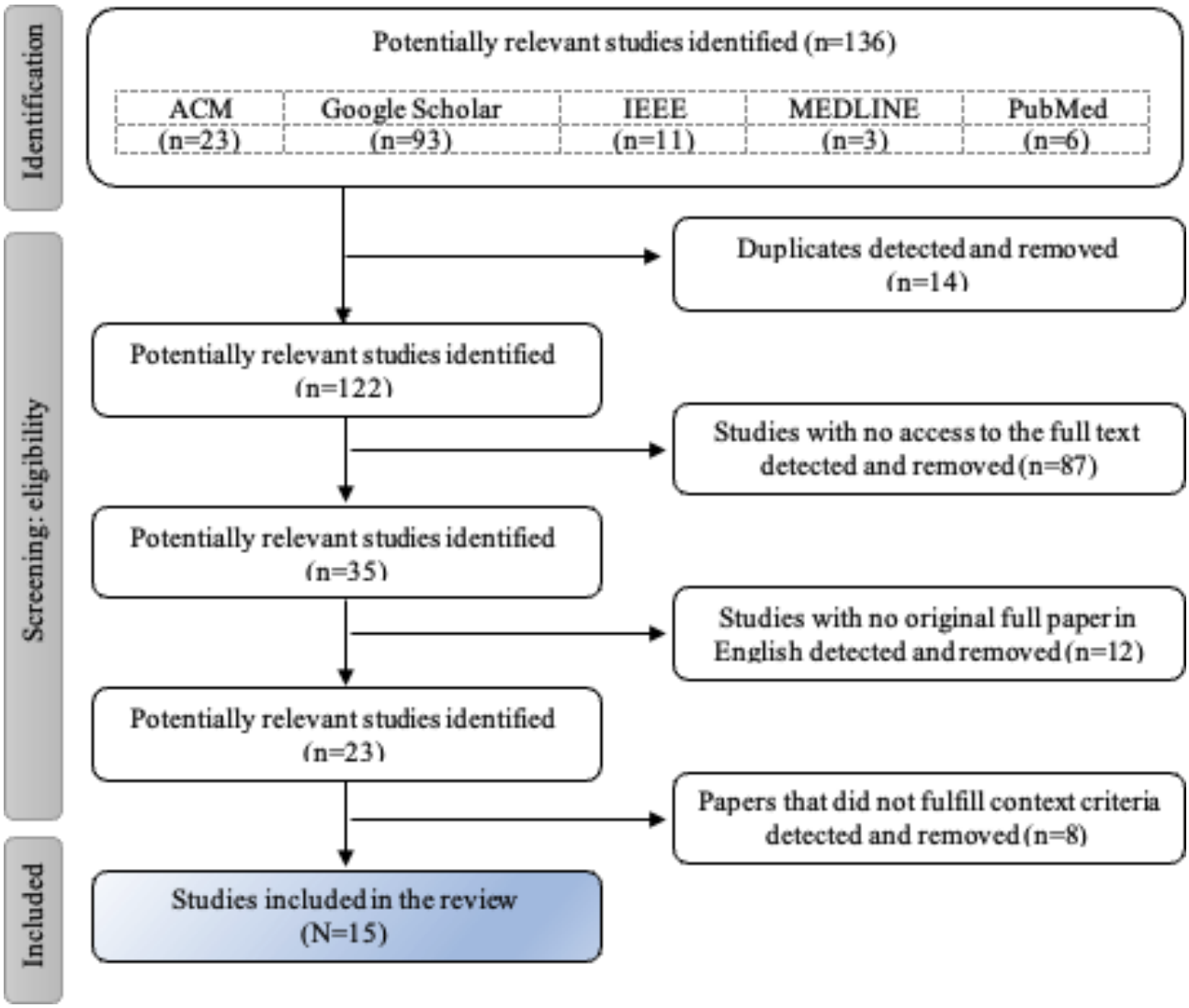

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Table . Sample characteristics, dementia types, and severity levels.

	Study	Sample	Type of dementia	Level of dementia	Experimental design	RT[a] intervention
1	Appel et al, 2020 [16]	8 females/2 males, mean age: 86.5 years	AD[b], FD[c], MD[d], and VD[e]	Mild to severe	Mixed methods design, and combined quantitative and qualitative data	A single up to 20-minute FI-VR[f] RT session, focusing on managing BPSD[g]
2	Appel et al, 2024 [28]	45 females/24 males, age: 65+ years	N/A[h]	Mild to severe	Mixed methods design, randomized controlled trial, and combined quantitative and qualitative data	1 - 3 FI-VR sessions lasting up to 20 minutes each, focusing on managing BPSD
3	Brimelow et al, 2020 [29]	9 females/4 males, mean age: 66 - 93 years	N/A	Mild to moderate	Mixed methods design; combined quantitative observation and qualitative interviews post a single VR[i] session	A single up to 5-minute FI-VR RT individual or group session, focusing on apathy and mood
4	Coelho et al, 2020 [30]	6 females/3 males, mean age: 85.6 years	N/A	N/A	Mixed methods design, and combined quantitative and qualitative pre- and postdata	A total of 4 sessions lasting up to 15 minutes each of personalized FI-VR tailored to participants' psychological needs
5	Ferguson et al, 2020 [31]	22 females/3 males, mean age: 85 years	AD, MD, and VD	N/A	Mixed methods design, and combined quantitative and qualitative data	A single up to 30-minute FI-VR RT session, focusing on the feasibility of the system
6	Huang and Yang, 2022 [32]	11 females/9 males, mean age: 79 years	N/A	Mild to moderate	Longitudinal observational study design, and quantitative data	A 10 to 12-minute FI-VR RT session held twice a week for 3 months, targeting cognitive function, global status, and depression
7	Kim et al, 2021 [33]	10 females, mean age: 85.80 years	N/A	Mild	Mixed methods design, and combined quantitative and qualitative data, including a survey to gather information about the psychological needs of each patient, to customize the system	1 - 2 sessions lasting 20 - 30 minutes each of personalized FI-VR tailored to participants' psychological needs
8	Klein et al, 2018 [34]	3 females/3 males, mean age: 74.67 years	N/A	N/A	Qualitative methods design, and combined observational data and multiple focus groups before the experiment to gather information about the needs of people with dementia, to design the system	A single 12 - 20 minute FI-VR RT session, focusing on efficacy and acceptance of the system

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	Study	Sample	Type of dementia	Level of dementia	Experimental design	RT[a] intervention
9	Manera et al, 2016 [35]	12 females/17 males, mean age: 76.3 years	AD and MD	N/A	Within-subject design, and combined quantitative and task performance data	A single 10-minute SI-VR[j] and controlled session, focusing on security, comfort, apathy, and anxiety
10	Moyle et al, 2018 [36]	7 females/3 males, mean age: 89 years	AD	N/A	Mixed methods design, and combined quantitative and qualitative data	A single up to 15-minute FI-VR RT session, focusing on engagement, apathy, and mood states
11	Ng et al, 2023 [17]	26 females/11 males, mean age: 65+ years	N/A	Mild	Nonrandomized controlled trial methods design and quantitative data	A single up to 12-minute FI-VR RT session, focusing on systems evaluation
12	Rose et al, 2021 [37]	2 females/6 males, mean age: 69.63 years	AD, FD, HD, and MD	Mild to severe	Mixed methods design, and quantitative observations and qualitative pre- and postdata	2 FI-VR RT sessions, lasting up to 15 minutes each, which focus on natural environments, aiming to reduce BPSD
13	Saredakis et al, 2020 [38]	10 females/7 males, mean age: 87.3 years	N/A	Mild to moderate	Mixed methods design and quantitative data	A single up to 20-minute FI-VR RT session, focusing on apathy
14	Saredakis et al, 2021 [39]	28 females/15 males, mean age: 84.8 years	N/A	N/A	Nonrandomized controlled trial methods design, and combined quantitative and objective data	A total of 3 FI-VR RT sessions, lasting up to 20 minutes each, focusing on apathy, cognition, depression, and quality of life
15	Tabbaa et al, 2019 [40]	2 females/6 males, mean age: 69.63 years	AD, MD, and VD	Mild to severe	Mixed methods design, and combined quantitative observations and qualitative pre- and postdata. A focus group was conducted before the experiment to gather information about the needs of people with dementia, to design the system	A total of 2 FI-VR RT sessions, lasting up to 15 minutes each, focusing on the technical aspects of the system, as well as its feasibility, acceptability, and practicality

[a]RT: reminiscence therapy.
[b]AD: Alzheimer disease.
[c]FD: frontotemporal dementia.
[d]MD: mixed dementia.
[e]VD: vascular dementia.
[f]FI-VR: fully immersive virtual reality.
[g]BPSD: behavioral and psychological symptoms of dementia.
[h]N/A: not available.
[i]VR: virtual reality.
[j]SI-VR: semi-immersive virtual reality.
[k]HD: Huntington disease.

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Study Characteristics

The present review analyzes 15 studies, and the participant demographics include both male and female people with dementia, with mean ages ranging from 65 to 89 years. Several studies focus on specific types of dementia, including Alzheimer disease, vascular dementia, frontotemporal dementia, and mixed dementia, whereas others do not specify the type of dementia examined. The studies reflect a range of dementia severity from mild to severe, though the majority emphasize mild to moderate cases [17,27,38]. A summary of the demographics of the reviewed studies is presented in Table 1.

Types of VR Systems, Levels of Immersion, and Virtual Environments Used in Dementia RT

The reviewed studies implemented 2 levels of VR immersion, as detailed in Table 2, with FI-VR being the most commonly used method, present in 12 of 16 studies. FI-VR necessitated the use of head-mounted displays (HMDs), such as Samsung Gear VR, Oculus Rift, HTC VIVE, Oculus Quest, Oculus Go, and Windows Mixed Reality headsets, to provide 360-degree panoramic views and interactive experiences [27,33,39]. For instance, one study used the Samsung HMD Odyssey Windows Mixed Reality with Leap Motion sensors (LM-010), allowing people with dementia to interact with the VR environment using hand gestures, including controlling seasonal transitions and engaging with animated objects [33]. Similarly, 2 other studies used the HTC VIVE Pro to simulate a familiar home environment, incorporating daily life objects and home appliances [17,32]. Several studies used Samsung Gear VR with a smartphone, allowing people with dementia to immerse themselves in calming virtual environments, including underwater scenes, travel destinations, and snowy landscapes [27,37,40].

In 2 reviewed studies, the content was mirrored on an external flat screen, allowing caregiver participation in providing reassurance and guidance during VR sessions [37,40]. Additionally, 1 study created their custom HMD featuring 180-degree projection to simulate time travel through various historical periods, including Berlin and Paris in the 20th century [34].

SI-VR was used in 3 studies where people with dementia experienced virtual environments on large projection screens rather than HMDs [35,36]. This approach allowed for limited interaction through a mouse, touchscreen, or sensor-based technology, while still providing an engaging experience. For example, 1 study used stereoscopic 3D screens paired with Volfoni Edge 1.2 active 3D LCD shutter glasses to deliver an SI-VR experience [35]. Lastly, 2 additional studies incorporated SI-VR, projecting the virtual forest onto a large display screen, with sensor-based interactions that allowed people with dementia to explore the river, trees, and surrounding environment [36] as well as familiar and unfamiliar environments [30,33]. Nonimmersive VR was not featured in any of the studies examined.

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Table . Apparatus and virtual environments.

	Study	Type of VR[a]	Virtual environment	Equipment
1	Appel et al, 2020 [16]	FI-VR[b]	Rocky lakeshore, forests, floating icebergs, and beaches	Samsung Gear VR and Sennheiser HD[c] 221 headphones
2	Appel et al, 2024 [28]	FI-VR	Calming in distinctive ways and nature visualization	Oculus Go with built-in and external Sennheiser HD 221 headphones
3	Brimelow et al, 2020 [29]	FI-VR	Underwater themes, beaches, farmyard animals, travel destinations, and snowscapes	Samsung Galaxy S7 and Samsung Gear VR headset
4	Coelho et al, 2020 [30]	FI-VR	Forests, beaches, cathedrals, childhood homes, workplaces, and religious venues	Samsung Gear VR and Oculus Rift VR
5	Ferguson et al, 2020 [31]	FI-VR	Beach scene	Mirage Solo with Daydream Business Edition
6	Huang and Yang, 2022 [32]	FI-VR	1960 - 1980 Taiwan: historical residence, radio, photo album, and feeding chickens	VIVE Pro
7	Kim et al, 2021 [33]	FI-VR	Streets of Memory, Nostalgic Youth, Homely Hometown, and Where I Want to Go	Leap Motion sensors and Samsung Odyssey Windows Mixed Reality Headset
8	Klein et al, 2018 [34]	Between SI-VR[d] and FI-VR	Time travel: Berlin (1970 - 1949), movie stars (1950s-1960s), television shows, and Paris in the 20th century	Custom-built HMD[e] (180-degree projection)
9	Manera et al, 2016 [35]	SI-VR	People	Barco OverView OLSF-721[f] full HD 3D stereoscopic LED video wall, Volfoni Edge 1.2 active 3D LCD shutter glasses
10	Moyle et al, 2018 [36]	SI-VR	Forest	Large screen
11	Ng et al, 2023 [17]	FI-VR	Early home environment: appliances and daily necessities	HTC Vive Pro and Leap Motion sensor
12	Rose et al, 2021 [37]	FI-VR	Nature and urban, forest, countryside, sandy or rocky beaches, and a cathedral	Samsung Gear VR and Samsung Galaxy S6
13	Saredakis et al, 2020 [38]	FI-VR	Personalized VR videos and places via Google Street View	Oculus Go
14	Saredakis et al, 2021 [39]	FI-VR	Personalized VR videos and places via Google Street View	Oculus Quest
15	Tabbaa et al, 2019 [40]	FI-VR	Cathedral, forest, sandy beach, rocky beach, and countryside	Samsung Gear VR and Samsung Galaxy S6 mobile phone

[a]VR: virtual reality.

[b]FI-VR: fully immersive virtual reality.

[c]HD: high definition.

[d]SI-VR: semi-immersive virtual reality.

[e]HMD: head-mounted display.

[f]OLSF: OverView LED Slim Front access.

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VRRT and the Role of Nature, Nostalgic Memories, and Social Themes

Overall, our review findings indicate that the virtual environments designed for RT were mainly created to be calming and engaging, with a strong emphasis on nature, nostalgic memories, and social themes (Table 2). RT via VR aims to create immersive, emotionally meaningful experiences that promote relaxation and memory recall and enhance engagement for people with dementia. Numerous studies demonstrated that virtual environments featuring peaceful natural landscapes, historical experiences, and familiar settings contribute significantly to the emotional and psychological well-being of people with dementia [16,17,27,31,32,34,36,38].

One of the most widely used themes in RT via VR was nature, as research indicates that natural landscapes help induce relaxation and reduce agitation in people with dementia [16,17,27,36,37]. It was found that people with dementia who experienced virtual forests, lakes, and beaches reported reduced anxiety and enhanced emotional engagement [16]. It was further highlighted that participants displayed lower distress levels when immersed in nature-based VR experiences, particularly those incorporating sensory elements such as bird sounds, flowing water, and open landscapes [28,37].

Nostalgic memories were another central element in RT in VR, as many virtual environments replicate meaningful locations linked to the people with dementia's past that can trigger autobiographical memories [27,31,32,34,38]. People with dementia responded positively to virtual environments that resembled places from their younger years, leading to enhanced memory recall and more profound personal engagement with caregivers and peers. These places included simulated childhood homes, nostalgic town streets, familiar workplaces, and meaningful travel destinations, including time travel experiences [27,30,33,37,40]. For example, people with dementia were immersed in "Streets of Memory," a VR representation of old neighborhoods and markets [33], past workplaces such as farms and factories [30], cathedrals and holy places [40], natural landscapes such as beaches and forests that evoked memories of youth [27,31,37,40], and rural settings from 1950 - 1970 [32,34].

Finally, it was observed that people with dementia were more likely to participate in discussions and share personal experiences when the virtual environments replicated familiar social places [30,31,33,37,40]. These places included, for instance, a VR Christmas dinner [31], a cathedral church service [37], a retired teacher who experienced a VR classroom [30], a familiar-looking café [33], and a personalized Google street view experience, where people with dementia could visit places they remember, such as old neighborhoods, vacation spots, and religious sites [38,39].

Feasibility and Impact of VRRT

Overall, the reviewed studies consistently demonstrated that VR for RT is feasible and can have a positive impact on enhancing emotional well-being and social engagement in people with dementia (Table 3). Several studies confirmed that people with dementia could successfully engage with VR without experiencing significant adverse effects [27,28,30,33,40]. However, minor side effects, including dizziness, nausea, and discomfort, were reported [27,33,38], though these were temporary and did not affect the overall feasibility.

Further to the above, several studies reported that people with dementia were able to engage with VR environments, often requiring only initial guidance or passive supervision. While explicit data on caregiver workload was limited, these findings suggest the potential for VRRT to be implemented with manageable facilitation demands in structured care settings [27,28,30,40].

Moreover, the flexibility of VR delivery formats, specifically the availability of both fully immersive and semi-immersive systems, emerged as a significant facilitator of feasibility. Fully immersive systems, such as HMDs, provide a deeper sense of presence and sensory engagement, which can enhance therapeutic outcomes. However, these systems often come with higher costs and setup requirements. In contrast, semi-immersive systems using large screens or projection displays offer a more accessible and logistically manageable alternative, particularly beneficial for individuals with mobility limitations or in resource-constrained care settings. This dual-modality approach increases the adaptability of VRRT, making it feasible across a range of environments, from long-term residential facilities to community-based programs [27,30,38,40]. In summary, the findings from multiple studies indicate that VRRT is feasible and well-tolerated, with adaptable delivery formats that are suitable for various care settings.

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Table . Reported side effects, feasibility, and outcomes of reminiscence therapy via virtual reality.

	Study	Instruments	Reported side effects	Feasibility or tolerance	Results
1	Appel et al, 2020 [16]	NPI[a], Confusion Assessment Method score, Montreal Cognitive Assessment, MMSE[b], recording instances of BPSD[c], and semistructured interviews.	Temporary feelings of dizziness and nausea.	People with dementia tolerated VR[d] well. VR is a feasible nonpharmacological intervention in acute care hospitals.	VR is a deployable, scalable, nonpharmacological solution for managing BPSD, which can significantly help dementia patients and their caregivers.
2	Appel et al, 2024 [28]	Quality of Life in Late-Stage Dementia Scale, nurses' daily notes for BPSDs and falls, and structured observations and interviews.	Two people with dementia experienced nervousness, anxiety, confusion, or disorientation, and 1 person with dementia experienced nausea.	People with dementia tolerated VR well. VR is a feasible nonpharmacological intervention in acute care hospitals.	VR is a safe, well-tolerated, and enjoyable nonpharmacological solution that can facilitate RT and significantly reduce aggressiveness in people with dementia.
3	Brimelow et al, 2020 [29]	PEAR[e], OERS[f], and structured observations and interviews.	Two people with dementia and impaired vision reported symptoms of cybersickness. One person with dementia found the headset slightly uncomfortable. Another person with dementia reported feeling "giddy," which was temporary upon device removal.	Mobile-based VR is feasible. People with dementia found VR enjoyable with low levels of physical and emotional discomfort.	The study found no impact on OERS measures; no significant increase in fear or anxiety. Reminiscence was observed in 6 of the 9 verbally communicative residents.
4	Coelho et al, 2020 [30]	Disability in daily activities (Barthel Index and Lawton and Brody Scale), Montreal Cognitive Assessment, Global Deterioration Scale, Cornell Scale for Depression in Dementia, NPI, SSQ[g], and EUROHIS-QOL-8.	N/A[h]	A feasible solution with no significant adverse effects related to simulator sickness or psychological and behavioral symptoms.	RT[i] via VR can benefit people with dementia, who are actively engaged in the sessions and share memories. No significant psychological or behavioral symptom changes were found.
5	Ferguson et al, 2020 [31]	Functional Assessment Staging Scale, PAINAD[j], and semistructured interviews.	Two people with dementia experienced worsened BPSD after VR exposure. Their PAINAD scores increased, indicating discomfort, distress, or pain.	VR is safe and enjoyable.	VR provides meaningful activity and enhances the quality of life for people with dementia.
6	Huang and Yang, 2022 [32]	Cognitive Abilities Screening Instrument, MMSE, Global status by Clinical Dementia Rating, and Depressive symptoms by the Center for Epidemiological Studies of Depression.	N/A	Feasible and well-tolerated.	RT via VR can improve mood and help preserve cognitive function in people with dementia during the intervention period.
7	Kim et al, 2021 [33]	MMSE, Activities of Daily Life, VR immersion scale, and observations.	Two people with dementia reported dizziness or nausea during VR exposure.	VR therapy was feasible and provided high satisfaction and immersion.	VR can be used to treat BPSD.

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	Study	Instruments	Reported side effects	Feasibility or tolerance	Results
8	Klein et al, 2018 [34]	Semistructured interviews and observations.	N/A	Feasible when special consideration is given to choosing personally relevant and engaging content, as well as the therapy's contextual factors.	VR can enrich traditional RT, foster conversations, and support positive interactions between caregivers and people with dementia.
9	Manera et al, 2016 [35]	MMSE, Clinical Dementia Rating Scale-Sum of Box scores, diagnostic criteria for apathy in clinical practice, and attention tasks.	Low levels of discomfort, anxiety, and fatigue.	People with dementia reported high satisfaction and security.	VR can have a positive impact on people with dementia experiencing apathy.
10	Moyle et al, 2018 [36]	OERS, PEAR, semistructured interviews, and structured observations.	Some participants experienced mild fear or anxiety during VR.	Feasible and well-tolerated.	VR was perceived to have a positive effect on people with dementia. However, compared to the normative sample, a greater level of fear or anxiety was observed during VR. It may have the potential to improve quality of life.
11	Ng et al, 2023 [17]	N/A	Dizziness as an effect of VR teleporting.	Feasible but complex.	The study supports the use of VR for RT in people with dementia.
12	Rose et al, 2021 [37]	OERS, OAS-MNR[k], St Andrews Sexual Behavior Assessment, time exposed, and semistructured interviews.	One person with dementia reported dizziness due to the frequent movement of the headset to and from their eyes.	The study provides evidence of the clinical feasibility of VR implementation in health care settings.	VR can enhance the emotional well-being of people with dementia.
13	Saredakis et al, 2020 [38]	Psychogeriatric Assessment Scale, AES[l], SSQ, Slater-Usoh-Steed Presence Questionnaire, Phonemic and Semantic Verbal Fluency Tasks, expectations or enjoyment measure, and structured interview.	A total of 35% (6/17) of participants experienced temporary side effects such as discomfort around the cheekbone, nausea, and dizziness.	RT via VR is highly feasible.	People with dementia showed improved semantic scores immediately after using VR for RT. Those with higher levels of apathy demonstrated the greatest cognitive improvements after VR-RT[m].
14	Saredakis et al, 2021 [39]	AES, Addenbrooke Cognitive Examination III, Geriatric Depression Scale, Quality of Life in Alzheimer Disease, Three-Item Loneliness Scale, SSQ, and structured observations and interviews.	Two people with dementia reported aftereffects (headache and head feeling heavy) that occurred in the evening following a morning VR session.	VR can be implemented in an aged care setting with appropriate protocols in place.	People with dementia enjoyed RT via VR.

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	Study	Instruments	Reported side effects	Feasibility or tolerance	Results
15	Tabbaa et al, 2019 [40]	OERS, OAS-MNR, semistructured interviews, and observational notes.	N/A	Feasible and well-tolerated.	VR enhanced the emotional well-being of people with dementia, with effects lasting for a short time after the session. VR also facilitated emotional openness between caregivers and people with dementia.

[a]NPI: Neuropsychiatric Inventory.
[b]MMSE: Mini-Mental State Exam.
[c]BPSD: behavioral and psychological symptoms of dementia.
[d]VR: virtual reality.
[e]PEAR: Person-Environment Apathy Rating.
[f]OERS: Observed Emotion Rating Scale.
[g]SSQ: Simulator Sickness Questionnaire.
[h]N/A: not available.
[i]RT: reminiscence therapy.
[j]PAINAD: Pain Assessment in Advanced Dementia.
[k]OAS-MNR: Overt Aggression Scale-Modified for Neurorehabilitation.
[l]AES: Apathy Evaluation Scale.
[m]VRRT: virtual reality reminiscence therapy.

VRRT and Its Impact on Emotional Well-Being

Emotional well-being is a vital aspect of dementia care, as people with dementia often face mood disturbances, anxiety, depression, and apathy. These issues are collectively known as the BPSD and can severely affect the quality of life of people with dementia [14,38]. Our review indicates that RT delivered through VR has been shown to have a positive impact on the BPSD, with numerous studies highlighting these benefits. Specifically, studies reported that the use of VR improved mood, reduced agitation, and increased engagement among people with dementia [27,31,35-38]. Additionally, RT via VR has been shown to alleviate emotional distress and psychological discomfort for both people with dementia and their caregivers, who were found to experience significant emotional relief and relaxation during VR reminiscence sessions [31,40], suggesting that VR can serve as a stress-reducing intervention.

One of the primary reasons RT via VR can enhance emotional well-being is its ability to immerse people with dementia in calming, familiar, or personally meaningful environments. Specifically, studies found that people with dementia who experienced VR environments depicting natural landscapes, such as forests, lakes, and beaches, exhibited increased relaxation and reduced anxiety [16,17,36]. Similarly, people with dementia who engaged in VR sessions featuring peaceful, scenic locations such as underwater themes, farmyards, or travel destinations displayed fewer signs of agitation and distress [27,34,38].

Furthermore, as with traditional RT, RT via VR can evoke deeply personal and emotionally meaningful experiences, which contribute to a sense of identity, self-awareness, and emotional fulfillment. It was observed that during RT in VR, people with dementia were able to restore memories from their past, triggering emotions tied to nostalgia, love, and belonging [39,40]. This emotional re-engagement often strengthens feelings of self-worth and dignity, which are crucial for maintaining well-being in dementia care [27]. To further support the above, another study found that VR reminiscence experiences elicited high levels of emotional satisfaction and security, with participants displaying more expressions of happiness and comfort compared to non-VR RT [35,37].

VRRT and Its Impact on Social Engagement

Social engagement is a crucial aspect of well-being for people with dementia, as it helps reduce loneliness, improve emotional stability, and strengthen relationships with caregivers and family members [38,41]. RT via VR has been shown to facilitate meaningful interactions by encouraging people with dementia to share personal experiences, engage in conversations, and participate in immersive social settings. Studies have consistently highlighted the ability of RT via VR to stimulate both verbal and nonverbal interactions, resulting in enhanced social connections [31,35,36,40]. To further support this, multiple studies observed that people with dementia who participated in VR reminiscence sessions were more likely to express emotions, initiate conversations, and reflect on past experiences. This enabled caregivers to gain deeper insights into their personal stories [39,40]. Additionally, research indicated that RT via VR enabled group discussions and storytelling, which encouraged people with dementia to comment on each other's experiences and engage in collective reminiscing, which reinforced social bonds [28,34,35].

Beyond verbal interactions, RT through VR also boosts emotional engagement, which plays a crucial role in maintaining social relationships [42]. Our review found that people with dementia who participated in RT via VR showed increased

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smiling, laughter, and eye contact, indicating greater emotional connectivity with those around them [36,39]. These findings imply that VRRT not only triggers memories but also fosters present-moment social interactions that contribute to emotional well-being.

Another significant way RT via VR enhances social engagement is by reducing social withdrawal and apathy, common symptoms in dementia that often lead to isolation [38]. A study found that people with dementia who participated in RT via VR exhibited lower levels of social withdrawal and depression, indicating that immersive experiences can encourage active participation in social interactions [27,37]. This aligns with findings from another study [40], which noted that VR-based RT provided a shared platform for communication, making it easier for caregivers and people with dementia to connect over mutual experiences.

VRRT and Its Impact on Cognitive Stimulation

While RT via VR has shown promising effects on emotional well-being and social engagement, its impact on cognitive function remains inconclusive. In particular, a study suggests that RT via VR may help preserve cognitive function during the intervention period, but its long-term effects are unclear, requiring further research to determine whether these benefits persist over time [32].

On the other hand, several studies found no significant improvements in cognitive domains such as attention, memory retention, or processing speed, nor sufficient evidence that VR-based RT reduces cognitive decline over time [27,35,37]. However, people with dementia with higher levels of apathy exhibited significant cognitive improvements following RT via VR, suggesting that the therapy may be particularly beneficial for specific subgroups [38,39].

One possible explanation for these findings is that RT via VR primarily stimulates emotionally charged autobiographical memories, rather than engaging higher-order cognitive processes such as reasoning, problem-solving, or working memory [35,39]. While RT is known to activate episodic memory networks, the extent to which these activations contribute to broader cognitive function remains uncertain [27,39].

Additionally, RT via VR was found to elicit autobiographical memories in familiar environments, reinforcing the importance of personalized content [30,33]. This suggests that the success of RT via VR may depend on familiarity with the virtual environment, with well-known settings enhancing reminiscence and memory recall more successfully than unfamiliar ones.

Current Limitations and Future Directions in VRRT

Despite the promising potential of using VR to enhance RT, several limitations hinder its widespread implementation in dementia care settings. One of the primary challenges identified in the findings is VR technology's high cost and resource-intensive nature. Many long-term care facilities lack the financial resources to invest in expensive VR headsets, high-quality software, and the necessary infrastructure for setup and maintenance [40]. While SI-VR solutions using large screens provide a more affordable alternative, they lack the same level of immersion and engagement as FI-VR [35,36]. Additionally, RT via VR requires dedicated space and structured session planning, which can be difficult for care facilities with limited resources and understaffed teams. To address these issues, research should focus on developing cost-effective VR solutions for RT, such as mobile-based VR apps and lightweight, affordable VR headsets that require minimal setup [36]. Additionally, open-source VR software and cloud-based VR platforms could reduce infrastructure costs and improve accessibility for lower-resource care settings [40]. Scalable VR solutions with portable, low-cost hardware and preprogrammed virtual environments could make VR more practical for widespread clinical use [37].

Another significant limitation is the technical complexity of VR systems and the need for caregiver training. Facilitating an RT session using VR systems involves specialized equipment that requires caregivers to be trained in setup, troubleshooting, and guiding people with dementia through VR experiences [27,40]. However, many caregivers report limited confidence in using technology, and the high turnover rates in dementia care settings make continuous training difficult [37,40]. To improve usability and adoption, VR developers should focus on creating simplified, user-friendly interfaces that caregivers can operate with minimal training [16]. Structured VR training modules for caregivers, including interactive tutorials and hands-on workshops, could further support the implementation of VR in dementia care [31]. Future research should explore the integration of voice-assisted navigation and automated session setup, allowing caregivers to facilitate VR for RT with minimal assistance [27].

The findings also indicate that people with dementia exhibit individual variability in their response to VR, with some experiencing sensory overload, disorientation, or fatigue, making it necessary to adjust VR exposure based on individual needs [27,28,31]. However, many VR systems in dementia care lack adaptive features that personalize the therapeutic content based on cognitive and sensory preferences. Thus, adaptive VR experiences that adjust based on people with dementia's emotional and cognitive responses could help tailor RT sessions via VR to individual needs, reducing the risk of sensory overload [33].

Additionally, there is limited research on the long-term effects of VR in RT and its ability to sustain therapeutic benefits over time. While multiple studies confirm that VR can improve RT's outcomes, there is insufficient evidence on whether it provides lasting improvements [27]. Most existing studies focus on short-term effects, with limited follow-up on how repeated exposure to VR influences neurocognitive resilience in people with dementia. Furthermore, the effectiveness of VRRT compared to traditional RT remains unclear, raising questions about its long-term clinical value and cost-effectiveness [40]. Future research should prioritize longitudinal studies that assess the sustained effects of VR in RT over time [35]. Lastly, comparative studies evaluating VRRT against traditional RT could provide deeper insights into its long-term therapeutic potential and clinical relevance [36,40].

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Discussion

Principal Findings

The findings of this review suggest that RT via VR is feasible and can positively enhance intervention in dementia care, with notable benefits in emotional well-being and social engagement. In particular, and in response to RQ1, it was found to be a feasible and well-tolerated intervention for people with dementia. Studies consistently report that people with dementia can successfully engage with virtual environments without experiencing major adverse effects. The availability of both fully immersive and semi-immersive systems enhances its adaptability, making it accessible for people with dementia with mild, moderate, and severe degrees of cognitive impairment and mobility limitations.

RT via VR has also been shown to enhance the health-related quality of life for people with dementia. In response to RQ2, the findings indicate that RT via VR addresses the BPSD by reducing agitation, anxiety, and apathy, while fostering relaxation and positive emotions, especially when immersed in peaceful, familiar, and personally meaningful VR environments. It is worth mentioning that the impact of RT via VR on cognition remains inconclusive. Studies examining its effects on memory recall, attention, and executive function found no significant improvements in cognitive performance. While RT via VR is able to stimulate autobiographical memory retrieval, it does not necessarily enhance long-term cognitive function or slow disease progression.

Comparison to Prior Work

The findings of this review are broadly consistent with recent reviews, both systematic and scoping, evaluating VRRT among older adults, including those with cognitive impairment. A systematic review [43] reported that VRRT is associated with emotional benefits such as reductions in anxiety, apathy, and depressive symptoms. Similarly, scoping reviews [26,27] found that immersive, autobiographically meaningful content tends to enhance mood and emotional engagement. However, this review also makes several distinct contributions to the literature. First, it focuses exclusively on people with dementia, while prior reviews included broader populations, such as older adults with or without cognitive impairment [26,27]. This more specific scope offers a dementia-targeted synthesis, enabling better applicability for practitioners and researchers in dementia care. Second, this review provides a more context-sensitive analysis of implementation challenges, extending beyond general usability concerns, identified in previous reviews such as simulator sickness, interface complexity, and the need for caregiver assistance [26,43]. This review builds upon prior usability discussions by identifying additional practical barriers that influence VRRT implementation, including the need for trained personnel, space constraints, and technical support requirements. While earlier reviews report general challenges, this review highlights how these factors can vary across care settings, suggesting the importance of context-specific implementation planning.

The cognitive outcomes reported remain limited across all reviews. While some evidence suggests that VRRT may stimulate autobiographical memory in the short term, none of the included reviews, including this one, found robust support for long-term improvements in memory, attention, or executive functioning. In previous reviews, the absence of randomized controlled trials to evaluate the solution has been emphasized [26,43], along with the need for more rigorous data [27]. Building on these insights, this review advocates for designing future studies around unified cognitive metrics and sustained postintervention follow-ups.

Lastly, this work offers forward-looking insights by providing practical, design-oriented recommendations, such as integrating mobile VR platforms, simplifying user interfaces, and creating culturally adaptive content libraries. These suggestions are aimed at addressing cost, accessibility, and caregiver usability gaps, areas not thoroughly operationalized in previous reviews [26,27]. As such, this review serves not only as a synthesis of existing evidence but also as a strategic roadmap for designing more scalable and feasible VRRT interventions explicitly tailored for dementia care.

Strengths and Limitations

This review provides a comprehensive synthesis of current evidence on the feasibility, acceptability, and therapeutic potential of delivering RT through VR for people with dementia. By incorporating studies that span varying levels of cognitive impairment and care environments, it offers a nuanced understanding of how both SI-VR and FI-VR technologies can be adapted to meet the complex and evolving needs of this population. A key contribution of this review lies in its focused analysis of critical dimensions often overlooked in prior reviews, including the degree of immersion, personalization, content relevance, and implementation challenges within real-world care settings.

To the best of our knowledge, this is the only recent review that concentrates solely on people with dementia, excluding broader populations of older adults with or without cognitive impairment, while examining the differential use of SI-VR and FI-VR systems. Moreover, by emphasizing system design considerations, the review aligns with contemporary calls for more inclusive, accessible, and person-centered VR interventions. These insights extend the review's relevance beyond clinical practitioners to include gerontologists, human-computer interaction researchers, and technology developers working at the intersection of dementia care and digital innovation. In doing so, it contributes a timely and interdisciplinary perspective that can guide the design, deployment, and evaluation of future VR-based therapeutic tools.

However, in response to RQ3, several limitations must be acknowledged. First, despite the promising findings, the high cost of VR equipment, software, and required infrastructure remains a significant barrier to widespread adoption, especially in resource-limited care settings. While semi-immersive systems may offer more accessible alternatives, they often lack the engagement and immersive quality necessary to maximize therapeutic effects. Second, the technical complexity of VR systems presents an operational challenge. Caregivers must receive adequate training to operate equipment and support

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people with dementia through virtual experiences, which may be unrealistic in understaffed environments.

Furthermore, many of the included studies are limited by small sample sizes, short intervention durations, and a lack of standardized outcome measures, which hinders cross-study comparability. Research on the long-term efficacy of VRRT is particularly scarce, with most studies focusing on immediate or short-term outcomes. The variability in individual responses also complicates implementation; while some people with dementia benefit substantially, others may experience sensory overload, fatigue, or disengagement. Current VR platforms generally lack adaptive features that can tailor the experience to individual user profiles or adjust dynamically in response to behavioral feedback.

In addition to the challenges identified in response to RQ3, this review itself is subject to several methodological limitations. First, the literature search was limited to freely accessible full-text papers published in English. As a result, relevant studies published behind paywalls or in other languages may have been excluded, potentially narrowing the comprehensiveness and representativeness of the findings. Second, the review was conducted by a single author, who carried out all stages of the process, including study screening, selection, and data extraction. While efforts were made to apply clear and consistent criteria throughout, the absence of a second reviewer may have introduced potential selection bias and reduced intercoder reliability.

Future Directions

To address RQ4, future research should enhance affordability, personalization, long-term impact, and usability of VRRT for people with dementia. Developing cost-effective, mobile-based VR solutions, such as lightweight headsets or tablet-compatible apps, could significantly enhance accessibility, particularly in underresourced care settings. These alternatives should aim to retain therapeutic immersion while reducing financial and infrastructural burdens associated with high-end VR systems.

Moreover, the personalization of VRRT experiences remains critical to their effectiveness. Future systems should integrate adaptive features that tailor content based on individual life histories, preferences, and cognitive or sensory needs. Approaches such as user-driven content selection, biometric feedback integration, and modular content frameworks can help dynamically adjust the experience to match user tolerance and emotional state.

To maximize real-world applicability, simplified interfaces and structured caregiver training protocols are necessary to reduce technical complexity and empower care staff. The inclusion of training toolkits, step-by-step onboarding modules, and in-app guidance systems could support smoother integration in everyday care workflows.

Importantly, research should also focus on establishing the long-term effects of VRRT through high-quality, longitudinal studies. These should investigate not only sustained psychological and cognitive outcomes but also the potential for reducing caregiver burden and improving overall health-related quality of life. Comparative trials between VRRT and traditional RT are also needed to clarify cost-effectiveness and relative efficacy.

Finally, co-design methodologies that involve people with dementia, caregivers, and interdisciplinary experts in the development process can ensure that future VRRT systems are ethically grounded, emotionally safe, and attuned to the lived realities of diverse dementia care populations.

Conclusions

In conclusion, this scoping review illustrates that the employment of RT through VR provides a viable and innovative strategy for dementia care. Nevertheless, practical challenges such as considerable costs, the complexity of personalization, and the necessity for caregiver training impede its extensive implementation within care environments. Notwithstanding these obstacles, the findings highlight the potential of VRRT to function as a scalable, person-centered tool in dementia care. Subsequent research that addresses usability, cost-effectiveness, and long-term outcomes, while integrating inclusive co-design methodologies, can contribute to the evolution of VRRT into a sustainable and equitable element in dementia care.

Data Availability

All data generated or analyzed during this study are included in this published paper (and its supplementary information files).

Authors' Contributions

MM conceived and designed this work, performed its data analysis and interpretation, and drafted the paper.

Conflicts of Interest

MM is an associate editor for *JMIR XR and Spatial Computing* at the time of this publication.

Checklist 1
PRISMA-ScR. PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews.
[DOCX File, 41 KB - xr_v2i1e73539_app1.docx]

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Abbreviations

BPSD: behavioral and psychological symptoms of dementia
FI-VR: fully immersive virtual reality
HMD: head-mounted display

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PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews
RQ: research question
RT: reminiscence therapy
SI-VR: semi-immersive virtual reality
VR: virtual reality
VRRT: virtual reality reminiscence therapy

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Youth and Young Adults' Perspectives on Augmented Reality–Driven Vaping Cessation Interventions: Interpretive Description Study

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Abstract

Background: Vaping among youth and young adults has become a significant public health issue, with increasing prevalence and associated health risks. Despite awareness of these risks, many youth and young adults struggle to quit due to complex social pressures, stress, and a lack of tailored interventions. Digital tools, including augmented reality (AR), offer an opportunity to address these challenges by creating engaging and personalized support systems.

Objective: The aim of this study was to determine what can be learned from youth and young adult vapers who are motivated to quit vaping to inform the design of mobile app–based AR intervention strategies.

Methods: This qualitative study applied an interpretive description (ID) approach to explore youth and young adults' perspectives on vaping cessation and their preferences for digital intervention features. Semistructured interviews were conducted with participants (N=12) who shared their experiences with vaping, quitting attempts, and ideas for app-based AR support. Reflexive thematic analysis and ID were used to code the data and identify patterns, resulting in the generation of themes that reflected the individualized and contextual nature of vaping cessation.

Results: The findings collectively yielded four major themes: (1) social and cultural context play a role in youth and young adults' experiences of cessation, (2) quitting vaping is an individual endeavor that does not always mean success, (3) digital support as a bridge between individual and social needs, and (4) AR as a catalyst for personalized support. These themes address the motivations, challenges, and opportunities identified by participants in their cessation journeys, as well as their perspectives on integrating AR technology as a supportive tool. Our findings reveal that vaping cessation is a deeply personal process influenced by internal motivations (eg, health improvement and personal milestones) and external factors (eg, social context). Participants identified AR as a promising app-based tool for cessation support, with interest in potential AR-integrated features such as gamified rewards, health visualizations, and anonymous support. Youth and young adults emphasized the need for sensitive design to avoid negative or punitive content.

Conclusions: This study provides actionable insights for designing youth and young adult–centered digital health tools that leverage app-based AR to support vaping cessation. By addressing the unique sociocultural and behavioral needs of youth and young adults, app-based AR interventions can bridge gaps in traditional cessation strategies. These findings contribute to the development of innovative public health approaches aimed at reducing vaping prevalence in vulnerable populations.

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KEYWORDS

vaping cessation; cessation support; augmented reality; AR; nicotine; nicotine dependency; youth; young adults; e-cigarettes; mHealth; apps

Introduction

Background

Vaping, particularly among youth and young adults, represents a growing epidemic with concerning health and societal implications. In Canada, the prevalence of vaping has risen sharply in the last decade, with 30% of adolescents aged 15 - 19 years and 48% of young adults aged 20 - 24 years reporting having ever tried vaping, and 13% and 18%, respectively, reporting vaping within the past 30 days [1]. These rates reflect a nearly 120% increase compared to prelegalization figures in 2017, underscoring the urgency of effective cessation interventions [2].

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Initially marketed as a harm-reduction tool for adult smokers, vaping has gained traction among nonsmoking youth and young adults due to its perceived safety, appealing flavors, and sleek, portable devices [3-6]. Social media, peer influences, and cultural norms further exacerbate the problem by glamorizing vaping as a socially acceptable behavior [6-8]. Emerging evidence highlights significant health risks associated with vaping, including nicotine dependence and respiratory and cardiovascular complications [9,10]. At the same time, Youth and young adults are navigating a broader mental health crisis, and many turn to vaping as a coping mechanism for stress and anxiety despite emerging evidence linking vaping to worsening psychological distress [11,12].

Despite increasing motivation to quit [13,14], many youth and young adults face unique barriers to cessation, including nicotine dependence, social reinforcement, and a lack of appealing support tools [5,15,16]. Traditional cessation methods, which are often adapted from adult-focused smoking programs, tend to be rigid, abstinence-oriented, and disconnected from the lived realities of youth and young adults. These approaches frequently neglect the digital and social contexts that shape youth behavior and fail to resonate with their preferences for nonjudgmental, flexible, and emotionally supportive tools [5,17,18]. Given this mismatch, there is a pressing need for novel, youth-driven solutions that prioritize harm reduction, self-compassion, and gradual behavior change.

Augmented reality (AR) represents a novel opportunity to meet these preferences. AR technology overlays digital elements onto real-world environments through smartphones or tablets, creating immersive and interactive experiences that can disrupt habitual behaviors and support real-time decision-making [18-20]. Parekh et al [21] present a systematic review and meta-analysis of AR applications in the sectors of entertainment or gaming, medicine, and retail, highlighting their widespread potential. Several popular mobile-based apps, including Pokémon Go, Snapchat, Google Maps, and Google Translate, use AR technology; however, many users may not be aware of this fact or the underlying principles of the technology. Vinci et al [18] argue that AR does not share some of the restrictions of other immersive technologies like virtual reality and can be more cost- and time-effective in development because only an object is created, not a whole scene; this may also lend to a higher degree of realism for the object.

Despite AR's potential, it remains largely understudied and underapplied in contemporary health interventions. Much of the research to date focuses on the application of AR to support smoking cessation. AR has demonstrated high usability, acceptability, and preliminary effectiveness in an app-based smoking cessation intervention using cue exposure therapy (CET) to disrupt associations between environmental triggers and cravings [20]. Building on these findings, Poudel et al [22] outlined a randomized controlled trial to evaluate an AR-CET app intervention at scale. Similar cue-reactive mechanisms have been documented in the vaping literature. Experimental studies demonstrate that exposure to vaping cues increases craving, attentional bias, and activation in reward-related neural circuits among young adults [23-25], providing evidence that vaping behavior is strongly cue-driven in ways analogous to smoking. Emerging evidence also suggests that repeated exposure to vaping cues may attenuate craving over time, supporting the theoretical relevance of CET-informed approaches for vaping cessation. Beyond CET, Wang and Yao [26] successfully used AR to increase the risk perception of vaping by enhancing introspective awareness and reducing temporal and hypothetical distances associated with the behavior. AR features may be especially valuable for youth and young adults, who are highly engaged with mobile technology and often prefer dynamic, real-world interventions over static educational resources [4,5,17,27,28].

To date, no research has explored the potential of app-based AR for vaping cessation, particularly among youth and young adults [29,30]. This study addresses this critical gap by investigating youth and young adults' perspectives, preferences, and experiences with vaping cessation to inform the development of AR app-based mobile interventions. By centring on the voices of youth and young adults, this research aims to advance the design of innovative, practical, and youth-driven digital tools to support vaping cessation.

Research Aim

This study aimed to explore the experiences and perspectives of youth and young adults who are motivated to quit vaping, with the goal of informing the development of AR-driven mobile interventions. By focusing on this demographic's unique needs, motivations, and challenges, the research aimed to generate practical insights that can guide the design of innovative and engaging cessation tools. The overarching goal was to identify key features and design considerations that would optimize the effectiveness and relevance of AR app-based interventions for youth and young adults.

Methods

Interpretive Description

This study used interpretive description (ID), a qualitative methodology designed to generate clinically relevant insights for applied health research [31]. ID is grounded in constructivist epistemology, which acknowledges that knowledge is co-constructed through interactions between researchers and participants. Unlike other qualitative methodologies that adhere to rigid theoretical frameworks, ID emphasizes flexibility, allowing researchers to explore both shared and individual experiences to develop actionable findings [31,32]. ID was particularly suited to this study's focus on vaping cessation among youth and young adults, as it enabled a nuanced understanding of their experiences and preferences within broader social and technological contexts.

Ethical Considerations

This study was granted ethics approval by the University of British Columbia Okanagan Behavioral Research Ethics Board (#H24-00545) in the spring of 2024. The recruitment process and all interview sessions occurred concurrently in the summer and fall of 2024. Informed consent was obtained from all participants, which was voluntary and revisited throughout the research process. Participants were provided with information pertaining to the study and a consent form embedded within the

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Qualtrics intake questionnaire. The consent form emphasized voluntary participation, the purpose of the study, potential risks, and the right to withdraw at any point without consequences. Participants were also informed about the potential emotional impact of discussing their vaping experiences, and support resources were shared. Youth and young adults were provided with an email to contact a researcher in case of additional questions or to receive more information about the study.

Participants and Procedure

Participants were purposively recruited to ensure alignment with the study's aims. Inclusion criteria were as follows: (1) aged 16 - 24 years, (2) currently vaping, (3) motivated to quit vaping, (4) proficient in English, and (5) residing in Canada. The inclusion criteria for this study ensured the relevance and feasibility of the research. Participants aged 16 to 24 years were selected because this age range represents a critical developmental period where vaping behaviors are often initiated, and cessation efforts are particularly impactful [16]. Additionally, this demographic represents Canada's largest population of vape users [1]. Requiring participants to be current vapers motivated to quit aligned with the study's focus on understanding vaping cessation. Motivation to quit vaping was assessed via a "yes or no" question on the intake screener.

Recruitment was conducted via professional networks, outreach to teachers and public health professionals, and email invitations to past research participants. Recruitment materials, including digital poster advertisements, were shared on social media platforms and via email lists. Many participants were recruited from a list of previous research participants in LS's laboratory who agreed to be contacted for future research. Past participants were contacted directly via the email address they had previously provided. Interested participants completed a Qualtrics survey to screen for eligibility and collect data on demographic characteristics, vaping history and behavior, dependence, motivation to quit vaping, app use, and familiarity with immersive technologies. Combining these items into a single Qualtrics survey (Multimedia Appendix 1) helped to streamline the process and prevent participant attrition. Researchers emailed interested participants who successfully completed the Qualtrics to schedule a Zoom (Zoom Communications, Inc) interview. All interviewed participants were offered honoraria (CAD $50 [US $36.31] e-gift card) for their time and contributions.

For ID, there is no preset quota for an appropriate sample size, as the focus is on generating rich, applicable insights rather than achieving statistical representation [31]. Rather than relying on data saturation, which assumes a finite set of themes that will eventually be exhausted, this study adopted the principle of information power [33]. Information power suggests that the more relevant and rich the data, the fewer participants are required, with sample size influenced by study aim, sample specificity, theoretical application, quality of dialogue, and analytical approach. The focused nature of this study, combined with a highly specific sample selected based on clear inclusion criteria, supported the feasibility of a smaller yet information-rich sample. Additionally, a manageable sample size enabled in-depth, inductive analysis, ensuring that the findings were meaningful rather than overly broad. Given the understudied nature of vaping cessation among youth and young adults, an initial estimate of 15 - 20 participants was made.

Data Collection and Analysis

Data were collected through semistructured interviews conducted via Zoom, ensuring flexibility and accessibility for geographically dispersed participants across Canada. Semistructured interviews were conducted using a carefully designed interview guide developed in collaboration with an interdisciplinary team and a youth co-researcher (Multimedia Appendix 2). The guide explored topics like participants' vaping behaviors, motivations for quitting, experiences with existing cessation resources, and perspectives on the integration of AR technology into vaping cessation interventions. To facilitate meaningful engagement and ensure informed discussions, participants were introduced to AR technology before the interviews. Recognizing that many individuals are unfamiliar with AR or confuse it with other immersive technologies, such as virtual reality, participants were sent a brief email explaining the technology. Participants were also encouraged to interact with a free AR app, such as Pokémon Go, prior to their interview session to provide a point of reference for the technology's capabilities, limitations, and potential applications.

The whiteboard function within the Zoom platform was leveraged during the semistructured interviews to further engage participants in the co-design process. Participants were shown the virtual whiteboard (Multimedia Appendix 3), which displayed four potential AR-based features, accompanied by brief explanations of each concept and supporting images. The proposed features were determined in collaboration with an interdisciplinary team member and computer scientist MKH. The goal of the whiteboard activity was to add clarity to the ideas and increase the interactivity of the interview [34]. To that point, Dewitz [34] highlights the potential of visual participatory approaches in enhancing interview settings and facilitating the gathering of rich data. Participants were asked to rank the four features (1=strongest idea to 4=weakest idea), and a screenshot of their choices was retained at the end of the interview.

All interviews were conducted by KF, each lasting approximately 45 - 60 minutes. With participants' informed consent, interviews were audio-recorded to ensure accurate and comprehensive capture of participants' narratives. All data were deidentified to protect confidentiality, and audio recordings were transcribed verbatim using Otter.ai. Transcripts were manually reviewed and corrected by KF to ensure accuracy and to achieve a high degree of familiarity with the data [31,35,36].

In ID, data are viewed as constructed rather than collected, highlighting the interpretive paradigm by reflecting the researcher's active role in choosing what counts as data and is subsequently analyzed as such [31,36]. Data were collected and analyzed concurrently to enrich data collection and analysis through this iterative process. After 10 interviews, no substantively new insights were emerging in relation to the research question. To ensure analytical rigor and confirm sufficiency, 2 additional interviews were conducted, reinforcing the determination that sufficient information power had been achieved. At this stage, further data collection was unlikely to

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yield significantly new perspectives while still maintaining feasibility within the study scope. By aligning with the principles of ID, information power, and reflexive thematic analysis (RTA), this approach ensured that the selected sample size struck a balance among data richness, methodological rigor, and practical constraints while allowing for a deep and meaningful exploration.

The data were analyzed using RTA, a qualitative method that aligns with ID by facilitating the exploration of complex and nuanced participant experiences [31,35,36]. RTA's flexibility and iterative nature allowed themes to emerge organically, capturing the depth of participants' narratives while addressing the study's objectives. Braun and Clarke's [35] six-phase framework guided the analysis process. First, familiarization with the data involved transcription and repeated readings of focus group and interview transcripts, during which initial impressions were documented in a reflexive journal. Coding was conducted manually to enable a deeper engagement with the data, while NVivo 14 software (Lumivero) was used to organize and manage codes. The coding process focused on identifying meaningful patterns and relationships relevant to the research questions. Initial codes were grouped into candidate themes, which were iteratively refined through reviews of transcripts and reflexive memos. Discussions between LS and KF further supported the refinement process, ensuring that the themes reflected participant perspectives and broader social and cultural contexts. Themes were then defined and named to capture their essence, integrating participant language where possible to maintain authenticity. The final themes were presented as a coherent narrative supported by illustrative participant quotes. The analytical approach emphasized rigor, reflexivity, and alignment with the principles of ID, ensuring that the findings offer actionable insights for designing youth and young adult–driven AR interventions for vaping cessation.

Gender-Based Analysis

Given documented gender-based differences in vaping behaviors [27], this study included an analysis disaggregated by gender to explore potential trends, such as variations in motivations for cessation or preferences for AR features. Gender was self-reported during demographic data collection, with all females identifying as women and all males identifying as men. Reflexive memos documented gender-related observations, which were revisited during theme refinement to ensure gendered patterns were considered.

Quality and Rigour

To ensure methodological rigor, the study adhered to Thorne's [31] quality criteria for ID research. Epistemological integrity was maintained by aligning the constructivist foundation with the study design and analysis. Representative credibility was achieved through purposive sampling and rich, thick descriptions of participant narratives, as well as triangulation between the interview transcripts, whiteboard interactions, and questionnaire responses. Analytic logic was demonstrated through an audit trail of decisions made during data collection and analysis. Finally, reflexivity was prioritized throughout the research process, with KF journaling reflections and acknowledging their positionality as a nurse researcher with a professional interest in vaping cessation.

Results

Description of the Sample

The findings (see Table 1) provide a detailed profile of the participants' vaping histories, cessation strategies, and primary motivations, offering valuable insights into the diversity of experiences within the study cohort. A total of 19 individuals completed the Qualtrics survey; however, 7 participants were lost to attrition due to either not responding to emails to schedule an interview or failing to attend their scheduled session. Participants (N=12, mean age 21.4 years) included a mix of self-identified genders (7 men, 5 women). The small sample size limited the capacity for a robust gender-based analysis, and no distinct trends were identified. This does not imply that gender differences are absent, but highlights the need for future research with larger, more diverse samples to investigate these nuances systematically. Participants indicated varying durations of vaping, ranging from 1‑3 years to over 3 years. The frequency of vaping also varied significantly, from occasional use (once per week or less) to several times per day. Cessation attempts were common, with most participants reporting 1‑4 attempts, although a few indicated more frequent efforts (5‑10 attempts). The strategies used were similarly varied, encompassing gradual reduction, cold turkey, cessation apps, nicotine replacement therapy, and professional counseling. Primary motivations for cessation spanned personal health concerns, financial pressures, social influences, and shifts in perceptions about vaping's appeal. The majority of participants indicated that they were somewhat familiar with AR technology and had some knowledge of its applications.

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Table . Participant characteristics and vaping history (N=12).

ID	Gender	Age (years)	Time vaping (years)	Frequency of vaping	Cessation attempts	Cessation strategies	Primary motivation	Familiar with AR[a] (no/somewhat/yes)
1	M	19	>3	Several times per day	1 - 4 attempts	Gradual reduction, cold turkey, and NRT[b]	Financial	No
2	M	21	1 - 3	About once per day	__[c]	—	Health	Yes
3	W	24	1 - 3	Several times per day	1 - 4 attempts	Gradual reduction, cessation apps, and NRT	Health	Yes
4	W	23	>3	Several times per day	1 - 4 attempts	Cold turkey, cessation apps, and NRT	Social pressures	Somewhat
5	M	22	>3	Once per week or less	1 - 4 attempts	Gradual reduction, NRT, and professional counseling	Health	No
6	W	21	>3	Several times per day	1 - 4 attempts	Gradual reduction, cold turkey, cessation apps, and NRT	Health	Somewhat
7	M	22	>3	A few times per week	5 - 10 attempts	Gradual reduction, cold turkey, and tolerance breaks	Health	Somewhat
8	M	21	1 - 3	Several times per day	1 - 4 attempts	Gradual reduction	Health	Somewhat
9	W	21	1 - 3	Several times per day	1 - 4 attempts	Gradual reduction and tolerance breaks	Health	Somewhat
10	M	18	1 - 3	Several times per day	1 - 4 attempts	Gradual reduction and tolerance breaks	Shift in perception	Somewhat
11	M	21	1 - 3	About once per day	1 - 4 attempts	Gradual reduction, tolerance breaks, and cessation apps	Shift in perception	Somewhat
12	W	24	>3	Several times per day	5 - 10 attempts	Cold turkey, cessation apps, and NRT	Financial	Somewhat

[a]AR: augmented reality.

[b]NRT: nicotine replacement therapy.

[c]Not applicable.

Qualitative Themes

The findings collectively yielded four major themes: (1) social and cultural context play a role in youth and young adults' experiences of cessation, (2) quitting vaping is an individual endeavor that does not always mean success, (3) digital support as a bridge between individual and social needs, and (4) AR as a catalyst for personalized support. These themes address the motivations, challenges, and opportunities identified by participants in their cessation journeys, as well as their perspectives on integrating AR technology as a supportive tool. To illustrate these themes, participant quotes support the results, which provide a nuanced understanding of their lived experiences and preferences. By grounding the findings in participants' voices, this section highlights critical insights to inform the design of engaging, practical, and youth and young adult–driven AR interventions for vaping cessation.

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Social and Cultural Context Play a Role in Youth and Young Adults' Experiences of Cessation

Participants described vaping as a normalized and pervasive behavior within their social environments, shaping both their initiation into the habit and their cessation attempts. Most youth and young adults indicated that they started vaping in social settings due to exposure, often viewing it as an expected part of social interactions. Vaping was frequently portrayed as an accepted and routine activity in many environments, creating a sense of normalcy that reinforced its persistence. When asked about their quitting journeys, many participants highlighted how their social environment and peers acted as barriers to cessation.

> *It's almost like there's like, a push not to quit [...] it's not that they're like, constantly telling me you shouldn't quit, but it's like, they'll offer me vapes constantly or something like that. So, it makes it harder, it's still doable, like you can always just say no, but it does make it much harder.* [#5, man, 22 years]

The normalization of vaping has created significant barriers to quitting, as participants often felt that ceasing to vape could isolate them socially or disrupt their sense of belonging. One participant expressed concerns about being excluded by colleagues at work, highlighting how social contexts can reinforce vaping behaviors and make quitting more difficult.

> *I feel like vaping is just a very normalized thing amongst young people [...] in my work, there's actually like a designated smoke space for people outside, they would go to smoke, and they would go to vape [...] I feel like stopping would make me kind of like a social outcast.* [#1, man, 19 years]

In many cases, participants deliberately distanced themselves from environments, social settings, or relationships that normalized or encouraged vaping. For some, this involved avoiding social gatherings or workspaces where vaping was prevalent, while for others, it meant disengaging from friendships with peers who vaped regularly. Although these measures were often helpful, they came with personal sacrifices: "My peer group has been negative. They haven't been helping. So, I've tried to cut some of them off" (#10, woman, 18 years). Such accounts underscore the relational complexities participants navigated in their efforts to quit. Another participant captured the nuanced interplay between family, peers, and environment, explaining:

> *It's a mixed support because my family are supporting me to quit vaping, and when I'm with them, the urge to vape is reduced, but when I go out and around my peers, I have the urge to vape. So, it depends on my location and the people around me.* [#9, woman, 21 years]

Beyond social normalization, vaping also emerged as a coping mechanism for many youth and young adults, particularly as a way to manage stress or emotional challenges. Participants described how stress from work, school, or personal relationships often drove them to vape, framing it as an accessible and socially acceptable method of self-soothing. One participant shared, "The moment I feel stressed, the only thing that comes to my mind is to go and vape" (#9, woman, 21 years), while another echoed this, stating, "Most times, when I'm sad, when I'm frustrated, the only thing that helps keep me calm is when I vape" (#8, woman, 21 years). This dual role of vaping as both a normalized social behavior and a tool for coping further entrenched its presence in participants' lives, making quitting especially challenging without alternative coping strategies.

Online platforms also played a dual role in participants' vaping experiences. Social media, particularly TikTok and Reddit, served as both a source of inspiration and a site of conflicting messages. For some, seeing influencers share their quitting journeys provided motivation: "There's a big wave on TikTok of influencers quitting vaping [.] that's helped me a lot" (#4, woman, 23 years). However, others noted that the glamorization of vaping on social media often undermined their efforts to quit.

Quitting Vaping Is a Personal Decision That Does Not Always Mean Success

Participants consistently emphasized the deeply personal nature of quitting vaping, highlighting how individual motivations, readiness, and self-efficacy shaped their cessation journeys. While external factors, such as social or familial pressures, sometimes influenced participants' decisions to quit, these were often secondary to internal drivers like health concerns or personal goals. Illustrating how the physical effects of vaping served as a powerful motivator, one participant described that:

> *My lung health in particular, I definitely have damaged lungs at this point. It's very hard to breathe [...] I'm out of breath when I go up the stairs, or if I'm walking at a faster pace, I definitely notice now it's harder to actually breathe and take deeper breaths than it was beforehand.* [#6, woman, 21 years]

Others framed their attempts to quit as milestones in personal growth, with one describing it as a personal goal: "I wanted to quit since the beginning of the year […] I saw it as a personal goal type of thing" (#5, man, 22 years).

Despite recognizing the importance of quitting, many participants acknowledged their success hinged on their confidence and readiness to commit to the process. One participant reflected, "It's really hard because it always comes down to me and me making up my mind" underscoring the centrality of self-efficacy in navigating cessation; they go on to add: "I feel like it has to be really my decision, and I'm not there yet" (#3, woman, 24 years), highlighting how personal readiness can act as both a catalyst and a barrier. External pressures, such as social disapproval or encouragement from family and peers, were recognized but rarely decisive. Participants stressed the importance of making their own decisions, emphasizing the individualized nature of quitting. One participant encapsulated this sentiment: "It has to be your decision. There is no one else who can do it for you" (#4, woman, 23 years).

Participants expressed a desire for recognition of small milestones in their vaping cessation journeys, emphasizing the

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importance of celebrating progress rather than focusing on setbacks. The pressure to succeed often felt overwhelming, particularly when relapses erased their "vape-free streak," which some described as belittling their overall efforts. This highlights the need for supportive approaches that frame quitting as a nonlinear process, allowing room for growth and resilience. While intrinsic motivation played a key role in initiating quit attempts, participants expressed that external reinforcement would be helpful in sustaining their efforts over time. Encouragement from peers, digital tracking of progress, and structured incentives were seen as important in maintaining motivation, particularly during periods of heightened stress or vulnerability.

Participants frequently used redirection strategies to manage cravings and navigate the challenges of quitting vaping. These approaches involved substituting behaviors, avoiding triggers, and restructuring their routines to reduce opportunities for vaping. Redirection was often seen as a practical and immediate method of coping, especially during moments of heightened cravings or emotional stress. A commonly reported technique was behavioral substitution, where participants replaced vaping with alternative activities or products. Simple actions such as chewing gum, using mints, or staying physically active were described as effective distractions during craving episodes; "How I cope is either a coping mechanism, like nicotine gum, mints, or distracting myself in some way" (#12, woman, 24 years). These substitutions served as manageable, low-barrier interventions, providing participants with tangible alternatives during moments of temptation. However, while these strategies were useful for managing immediate cravings, participants noted that without external reinforcement, it was difficult to sustain momentum over time, reinforcing the need for structured, ongoing support.

Reliance on self-discipline and willpower alone was frequently associated with challenges and relapses. Participants who attempted unassisted cessation methods, such as quitting "cold turkey," often found the process unsustainable. While some expressed a desire to take control of their behavior independently, they acknowledged the difficulty of doing so without external support or tools: "Cold turkey takes a lot of willpower [.] It's not something you can just wake up one morning and do" (#1, man, 19 years). These perspectives exemplify the limitations of self-reliance, particularly when facing strong nicotine cravings or deeply ingrained habits. As such, many participants expressed a desire for digital interventions that not only supported self-directed quitting but also provided extrinsic motivators, such as virtual rewards, positive reinforcement, and social accountability, to sustain long-term cessation efforts.

Digital Support as a Bridge Between Individual and Social Needs

Participants highlighted the potential of digital tools to address the dual needs of individual autonomy and social connection in their vaping cessation journeys. Digital interventions, such as mobile apps, were seen as capable of personalizing the quitting process while offering supportive, nonjudgmental spaces for connection with others. Many participants appreciated the adaptability of these tools, emphasizing the importance of features that cater to their individual progress and goals. That said, most participants disclosed little experience engaging with currently available mobile-based vaping cessation apps. When questioned about why they did not use apps in their quit journeys or their general opinions on cessation apps, youth and young adults shared a lack of knowledge about existing apps, a lack of confidence in the effectiveness of vaping cessation apps, and a lack of sustained engagement with the apps they had tried. This lack of confidence stemmed in part from perceptions that existing tools were outdated, impersonal, or not tailored to the realities of current vaping products or youth and young adults' experiences. One participant shared their previous experience with an app, stating:

> *I think the technology wasn't there for it. I just think it wasn't as up to date as it should have been [...] it was more catered to, like older style vapes and less like the newer disposable kind.* [#4, woman, 22 years]

Building confidence in AR-based interventions will require addressing these gaps by ensuring relevance, personalization, and innovation. Participants indicated that future tools must feel current and responsive in terms of technology and content and include features that reflect the modern vaping landscape, such as support for disposable vape cessation, real-time feedback, and interactive engagement. Additionally, establishing credibility through trusted partnerships, transparent design, and co-creation with youth and young adults may help foster greater trust and perceived efficacy. That said, several positive attributes of potential app-based interventions were discussed.

For participants who valued anonymity, digital platforms offered an intriguing means of connecting with peers facing similar struggles without fear of judgment. Features like anonymous forums for peer support within apps were especially appealing, as they allowed participants to feel less isolated in their journeys. One participant explained:

> *[It] doesn't have to be like something like super, super social, but, you know, just reading other people's experiences, maybe talking about your experience, that kind of stuff. I think that's important.* [#5, man, 22 years]

Many youth and young adults emphasized the need for a balance between social connection and privacy; this blend of community and privacy was viewed as a critical strength of digital tools, particularly for youth and young adults navigating the stigma surrounding vaping. While traditional peer interactions in person could reinforce vaping behaviors, structured, judgment-free digital communities were seen as a way to foster motivation and reduce feelings of isolation. This blend of community and discretion was identified as a crucial strength of digital interventions, particularly for youth and young adults navigating the stigma surrounding vaping and the complexities of quitting within their social environments.

Participants were particularly interested in the potential of incentives to enhance their vaping cessation efforts, viewing rewards as motivating and affirming their progress. Many appreciated the idea of earning in-app currency that could be used for virtual rewards or gamified features, fostering a sense

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of achievement and making the quitting process more engaging. Tangible incentives, such as e-gift cards, were perceived as especially appealing, offering practical and immediate benefits that reinforced their commitment to staying vape-free. A participant highlighted this interest, stating:

> *When I heard virtual rewards and incentives, I got so hyped up [...] one thing I think would be effective was, if you go a certain amount of days without vaping, your virtual reward could be an entry for an even bigger prize [...] I think that having contests and having, you know, things of that nature will be beneficial. I think that also providing gift cards and, you know, coupons and discounts and all of those things, they will definitely help.* [#1, man, 19 years]

Participants emphasized that incentives could create a positive reinforcement loop, celebrating progress while encouraging continued effort. Youth and young adults were open to abstinence verification with methods like saliva cotinine testing, thus highlighting an interest in app-based contingency management (CM).

Digital tools were also recognized as a platform for reflection and growth. Features such as journaling, self-reflection prompts, and progress visualization to understand their behaviors better and celebrate milestones; "kind of reflect on, oh, I've made it this far, you know, like I could keep going and use that as a motivator" (#6, woman, 21 years). Several participants emphasized the need for content that is positively framed. App-based tools were ultimately viewed as an opportunity to bridge the gap between self-directed quitting and the need for external encouragement, creating a holistic support system.

AR as a Catalyst for Personalized Support

Overview

Participants endorsed AR as a unique and innovative tool for enhancing their vaping cessation journeys by offering support and distraction during moments of vulnerability. AR's immersive and interactive nature has the potential to allow participants to engage with interventions in ways that feel dynamic, responsive, and motivating. Participants ranked proposed AR-based features through a Zoom whiteboard activity, emphasizing their preferences for tools that combine motivation, engagement, and practical support. The rankings reflected strong enthusiasm for gamification and virtual rewards as the most desirable features, highlighting the appeal of progress tracking and achievement-based incentives. This is followed by health effects visualization, interactive quitting support, and trigger identification and management, reflecting a desire for educational reinforcement and real-time coping mechanisms. These findings underscore AR's potential to provide a holistic, engaging, and youth-centered approach to vaping cessation by making support accessible and immersive, particularly during the most vulnerable moments of the quitting process.

AR as a Conduit to Nonjudgmental Real-Time Feedback

The potential for AR to provide nonjudgmental, anonymous support resonated with participants. Interactive elements, such as artificial intelligence (AI)–powered avatars or real-time feedback, were viewed as desirable for those seeking guidance without fear of stigma.

> *I might find myself in a situation where I have nobody to talk to about this, where I'm too embarrassed to talk about this, you know what I mean, like, and then if I have [...] AI or a real human who is qualified to talk about this, I do think that would be a helpful thing.* [#7, woman, 22 years]

For some, AI-based interactions were preferable to human-led support, as they offered privacy, autonomy, and an escape from social judgment. Others, however, valued the "human-like" presence an AR avatar could simulate during moments of need, appreciating the blend of technological convenience with empathetic support. Not all participants trusted AI, with some expressing a preference for human-led interactions, such as those with counselors, due to the nuances, emotional depth, and authenticity of human conversations. To foster trust in future AR applications that incorporate AI, participants emphasized the importance of transparency in how AI functions, the ability to customize or opt into human support, and ensuring that AI interactions feel empathetic rather than robotic. Hybrid models, which allow users to choose between AI-driven guidance and human-led support, may offer the flexibility and emotional safety needed to meet diverse preferences, thereby increasing user trust and sustained engagement.

Participants emphasized the importance of tailored content and motivational messaging in maintaining engagement and supporting long-term cessation. Personalized, positively framed reminders and notifications were seen as essential tools for reinforcing motivation without inducing guilt or shame. Rather than punitive or negatively framed alerts, participants preferred encouraging messages that acknowledged progress and reinforced their reasons for quitting. One participant suggested:

> *A feature that could give motivational affirmations for the day, like you don't have to wait today, like some of motivation that comes up pops up every day on my app to keep me motivated not to go back to vaping or stuff like that.* [#9, woman, 21 years]

Features such as customizable reminders, goal setting, milestone celebrations, and daily motivational messages were viewed as ways to sustain engagement while making the quitting process feel supportive rather than restrictive. AR's ability to deliver real-time, interactive reinforcement, such as visual progress tracking or immersive encouragement from an AI avatar, positions it as an ideal tool for keeping users motivated and engaged in a way that feels personalized, empowering, and nonjudgmental. One participant underscored the importance of personalization in making the intervention feel meaningful:

> *I think that personalization is definitely going to be the core of this app [...] I think that that should be kind of the leading principle of the app, I think you should have the right to choose.* [#1, man, 19 years]

Another participant highlighted the importance of individualized goal setting, reinforcing the need for an intervention that adapts to the diverse experiences of users:

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> *Everybody has their own, like, goals, right? Everybody has their own little path that they're on. And if, for me, not vaping for two weeks is a big goal, it might not be for somebody else who's hasn't been vaping for like, three years, you know what I mean?* [#7, man, 22 years]

These findings emphasize that offering multiple support formats, ranging from AI-driven assistance to human-led interactions, is crucial to accommodating diverse user preferences. While some participants prioritized privacy and anonymity, others sought genuine human connection, reinforcing the need for flexibility and choice in digital cessation interventions. By fostering a personalized, stigma-free, and engaging support system, AR has the potential to transform vaping cessation into a more interactive, accessible, and user-driven experience.

AR as a Tool for Distraction and Motivation

Participants viewed AR's gamification capabilities as a compelling way to support their cessation efforts, with the potential to both distract them from vaping and motivate them on their journey. AR was uniquely positioned to provide structured engagement during cravings, transforming vulnerable moments into opportunities for reinforcement. Interactive games or immersive environments could serve as a constructive alternative to vaping, helping participants navigate stress and temptation. One participant captured this sentiment by explaining how AR could serve as an immediate, accessible distraction: "If you feel a craving, you open the app, and you have somewhere to go and something to do" (#12, woman, 24 years); another shared a similar thought saying, "an app like this [would] come in handy in case of situations where I would be tempted to vape" (#9, woman, 21 years). These elements aligned closely with participants' broader use of behavioral redirection strategies, offering a structured and engaging way to manage cravings.

Many participants described the need for interactive and rewarding elements that could transform quitting from a rigid, pressure-driven task into an engaging and reinforcing experience. One participant highlighted this point, sharing that "the gamification and like the rewards and that kind of stuff that can be something that would make me stay more [consistent]" (#5, man, 22 years). Gamification through features such as progress tracking, interactive challenges, and virtual rewards were particularly appealing for their ability to reinforce positive quitting behaviors while making the process feel more like a game than a struggle.

Participants envisioned gamification as a blend of competition, community, and engagement, drawing inspiration from popular mobile games. One participant described how AR-based features could create a social yet anonymous competitive element, likening it to games such as Hay Day or Farmville, where users can build progress over time and engage in friendly competition:

> *I love that idea. It kind of like, in my mind, the way that I like think about it is, like AR Hayday or Farmville [...] there's like, a social aspect to that where, like, you compete with people and you grow your farm or whatever [...] you can kind of, like, make it a competition with your friends or whatever, and grow a community that way, but also have that anonymous, like, just that random person across Canada that you could just battle it out with for most days that you're not vaping, which I think is really cool.* [#4, woman, 23 years]

By integrating leaderboards, virtual rewards, and community-driven challenges, AR could provide both an emotional incentive and a distraction during cravings, reinforcing progress in an engaging and interactive way. However, participants emphasized that gamified elements should be designed thoughtfully and sensitively to avoid discouragement. One key concern was handling setbacks, as overly punitive design choices, such as resetting progress entirely after a relapse, could undermine confidence and motivation. One participant stressed the importance of maintaining momentum even after a lapse:

> *If I do all of a sudden vape, I'm not going to obviously continue earning points, but I don't lose all of them, or, like, I just don't lose my progress, is what I'm saying. I just don't want to lose all progress just because I made a mistake and just because I did what I did.* [#7, man, 22 years]

These findings highlight the delicate balance needed in designing gamified interventions for vaping cessation. AR-based tools must provide engagement, distraction, and reinforcement without introducing discouraging setbacks that might deter continued efforts. A well-designed system that celebrates progress, fosters competition and community, and offers flexible, forgiving incentives has the potential to make quitting feel like an achievable and rewarding challenge rather than an isolating struggle.

AR Meets the Desire for Education and Real-Time Coping Mechanisms

Another valued feature of AR was its potential to provide health visualizations, offering users a dynamic way to track the benefits of quitting. Unlike static educational content, AR has the ability to immerse users in a personalized, real-time experience, reinforcing tangible progress in a visually engaging manner. Participants expressed interest in seeing how their lungs and body could heal over time, believing this could serve as a motivational tool to sustain their quit attempts. One participant emphasized the power of real-time feedback, explaining, "I think having that visualized in AR would be also beneficial, so that people could kind of see their progress on their own body in kind of real time as it were" (#12, woman, 24 years). Another participant appreciated the positive framing of such a feature, remarking, "I like the idea of it, like showing the effects of quitting, because then it's not just like, Oh, you're doomed, you know?" (#5, man, 22 years). However, some participants noted the need for balance, cautioning against overly graphic or negative imagery that could provoke fear or denial. This highlights the importance of creating visualizations that are both impactful and user-sensitive. Participants also indicated that an AR visualization feature on its own may not be enough to sustain user engagement, but it would be a useful educational feature when integrated into a more holistic app.

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CET was introduced as a potential feature to help desensitize users to vaping triggers, but participants expressed strong skepticism about its effectiveness in the context of vaping cessation. Many feared that deliberately exposing themselves to cues such as virtual vaping devices or smoking scenarios could be counterproductive, intensifying cravings rather than reducing them. One participant described their discomfort with being reminded of vaping, stating:

> *I can't even look at a vape because it just immediately, like, reminds me of it, and then I start thinking about it [...]. I just start, like, hyper fixating on it [...] it makes the cravings worse [...] I personally wouldn't open that feature and like try to see a cue, just because I know that it would just make me think about it, and it would just make everything worse.* [#6, woman, 21 years]

Another participant echoed this sentiment, saying:

> *[It's] going to make me more agitated for vaping somehow [...] even seeing vapes on phone is just going to, like trigger me more to go to what I'm trying to quit.* [#11, man, 21 years]

This skepticism reflects a broader hesitation around strategies that may feel emotionally taxing without clear evidence of their effectiveness in the context of vaping cessation. Despite concerns around CET, participants expressed strong interest in educational tools that help them identify personal triggers and develop actionable strategies for managing them. Rather than confronting triggers head-on, participants preferred interventions that provided personalized coping mechanisms. One participant shared the importance of practical alternatives, sharing a desire for learning:

> *Different actual things you can do in the moment [...] techniques [like] you can just grab a water bottle with a straw or some like something like that.* [#4, woman, 22 years]

While another participant indicated a desire to learn more about their personal triggers, "something that helps me is to become aware of, like, I guess, my triggers" (#5, man, 22 years). Participants valued the idea of combining personalized insights with practical suggestions for overcoming challenges, which could enhance their understanding of their vaping behaviors and empower them to develop healthier coping mechanisms.

These findings suggest that AR could play a critical role in trigger management, not just through direct cue exposure but by integrating real-time insights and behavioral guidance. For instance, AR could help users log their triggers, recognize patterns over time, and receive tailored coping suggestions in response to their cravings. By combining personalized insights with practical, interactive solutions, AR has the potential to empower users to understand their vaping behaviors, build self-efficacy, and develop healthier coping mechanisms that support long-term cessation success.

Discussion

Primary Findings

This study explored the perspectives of youth and young adults on vaping cessation, emphasizing the potential role of digital interventions, including AR, in supporting their cessation journeys. Using ID, the findings highlight the multifaceted influences shaping cessation behaviors, including technological, relational, and individual factors. Four themes were co-constructed: (1) social and cultural context play a role in youth and young adults' experiences of cessation, (2) quitting vaping is an individual endeavor that does not always mean success, (3) digital support as a bridge between individual and social needs, and (4) AR as a catalyst for personalized support. These findings underscore the complexities of vaping cessation and the opportunities for innovative, youth and young adult–centered interventions that align with young people's digital habits, motivations, and support needs.

Stepping back from the individual themes, this study makes a broader contribution to the literature by proactively ensuring that youth and young adults' needs and preferences are embedded into intervention designs from the outset. Many existing vaping cessation interventions are developed with limited engagement from young people [28], potentially restricting uptake and effectiveness. By using ID, a methodology that prioritizes applied health research, this study was able to generate practical, actionable recommendations that align with youth and young adults' lived experiences, digital habits, and cessation challenges. Theoretical frameworks for user-centered design, such as the Information Systems Research framework [37] or the BUS Framework, which incorporates principles from Behavior change theories, user-centered design, and Social marketing [38], can guide the integration of youth and young adults' perspectives into digital health design, thereby ensuring that future interventions are not only evidence-based but also user-centered, increasing their potential for engagement, relevance, and long-term success.

The first theme emphasized the pervasiveness and normalization of vaping within youth and young adults' social environments, reinforcing both initiation and continued use. Many participants started vaping in social settings, where it was framed as an expected part of social interactions, making cessation particularly challenging. The normalization of vaping was not only a driver of use but also a barrier to quitting, as participants reported experiencing peer influence, social expectations, and fear of social exclusion if they stopped vaping. These findings align with prior research showing that peer reinforcement plays a critical role in youth and young adults' vaping behaviors [3-7]. Similar to Rahman et al [28], many participants attempted to distance themselves from social settings where vaping was prevalent, but this often resulted in social disconnection, reinforcing the need for cessation interventions that provide alternative forms of social support without requiring them to disengage from their social lives entirely.

Quitting vaping was described as a deeply personal and nonlinear process driven primarily by intrinsic motivations such as improving health, achieving personal milestones, or

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addressing financial concerns. This aligns with Self-Determination Theory [39], which highlights the role of autonomy and intrinsic motivation in sustained behavior change. While external pressures, such as encouragement from family or disapproval from peers, played a role in some participants' decisions to quit, self-efficacy and personal readiness emerged as the most critical factors for success in theme two. Many participants described the push-pull nature of cessation, where they oscillated between the desire to quit and difficulties maintaining abstinence, often cycling between quit attempts and relapse. This reinforces the need for cessation interventions that are flexible and adaptable, allowing users to engage at different stages of readiness without being penalized for setbacks. While intrinsic motivation initiated the quitting process, participants emphasized that sustaining long-term abstinence required external reinforcement, such as celebrating small wins and receiving positive social support. These findings suggest that effective cessation tools should cultivate self-determined quitting efforts and integrate structured external reinforcements, such as peer accountability, personalized encouragement, and digital incentives, to help individuals remain engaged and resilient throughout their quit journey.

Importantly, the findings also point to the limitations of hard deadlines or rigid abstinence expectations for this population. Participants described traditional cessation models as often misaligned with their lived experiences, this may be particularly pronounced given the mental health challenges many youth and young adults face. This aligns with recent research analyzing Reddit posts about quitting vaping, where young adults emphasized the importance of self-love, self-grace, and a harm reduction mindset over perfectionism [17]. Rather than promoting immediate abstinence, participants preferred compassionate, flexible approaches that framed quitting as a gradual process. Digital cessation tools that offer positive reinforcement, celebrate small steps, and normalize nonlinear progress may be especially effective for supporting young people navigating emotional, social, and behavioral complexities in their quit journeys.

Aligned with both themes 2 and 3, participants expressed a desire for progress tracking and milestone recognition, reinforcing research on positive reinforcement and gain-framed messaging in behavior change interventions [16,27,40]. These findings underscore the importance of integrating and balancing intrinsic and extrinsic motivation in digital cessation tools, ensuring that interventions celebrate progress rather than focusing solely on quitting as an all-or-nothing goal. Intrinsically motivated participants found personalized goal setting, self-reflection tools, and progress visualization to be meaningful motivators, reinforcing their sense of autonomy and self-efficacy. Others were more extrinsically motivated, responding positively to the potential for incentives, social reinforcement, and gamification elements, highlighting the importance of offering diverse engagement strategies within cessation interventions. By integrating multiple forms of motivation, digital cessation tools can increase engagement, enhance long-term commitment, and better support the diverse needs of youth and young adults navigating their quit journey.

Findings from the third theme suggest that digital tools are viewed as a potential bridge between individual autonomy and social connection, offering customizable, nonjudgmental, and interactive support. Participants reported limited engagement with existing vaping cessation apps, citing a lack of awareness, skepticism about effectiveness, and difficulties maintaining engagement. This aligns with prior research indicating that many available app-based vaping cessation tools lack user-centered design and may fail to address many of the essential components of cessation, such as coping strategies for withdrawal or relapse prevention, reducing their long-term efficacy [41,42]. Despite this, participants still viewed digital platforms as promising tools for personalized support, including peer-driven support networks, where they could connect with others anonymously and without stigma. This aligns with Huma et al [27] and Rahman et al [28], who emphasized the importance of socially connected, nonjudgmental spaces in digital cessation interventions.

Participants were divided in their preferences for AI-driven versus human-led support, highlighting the need for flexibility in interventions. Some valued AI-driven interactions, such as chatbots or virtual avatars, are appreciated for their immediacy, privacy, and nonjudgmental nature, making them useful for on-demand support during cravings. Others preferred human-led interactions, emphasizing the emotional depth and relatability of counselors or peer mentors. Underlying themes 3 and 4, many participants emphasized privacy as paramount to ensure users feel safe and supported while engaging with these tools. As such, transparency in data collection and usage practices would be essential to building trust and encouraging sustained engagement among youth and young adults.

The final theme positioned AR as a uniquely valuable tool for vaping cessation; unlike traditional cessation approaches, which often rely on rigid goal setting and self-discipline, AR can facilitate adaptive, personalized support, integrating features such as gamification, behavioral tracking, and AI-powered coaching by superimposing digital images and objects into the user's real environment. AR can also provide distraction, a key facilitator to quitting identified by Al-Hamdani et al [43], Pbert et al [16], Rahman et al [28], and Struik and Yang [17], offering youth and young adults somewhere to go during times of heightened cravings and stress. Participants expressed enthusiasm for gamified features, such as progress tracking, virtual rewards, and interactive challenges, which have been highlighted as ways to improve user experience and enhance engagement with digital health interventions [44-48].

The findings align with existing cessation literature, which identifies goal setting, self-monitoring, and social support as common behavior change techniques (BCTs) for smoking cessation success [49,50]. BCTs refer to an intervention's specific, active components that aim to influence behavior by targeting psychological or contextual mechanisms of change [51,52]. McKay et al [41] highlight the need for vaping cessation apps to use specific BCT-based features known to support quitting. The strong emphasis participants placed on personalized goal setting and progress tracking in this study reflects BCTs such as "goal setting (behavior)" and "self-monitoring of behavior," both of which have been

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implemented in successful smoking cessation interventions and have been shown to enhance user engagement and quit outcomes [49,50]. Similarly, the desire for positive social reinforcement and community-based encouragement resonates with BCTs categorized under "social support," which were not only present across all of the Canadian smoking cessation websites analyzed by Struik et al [53] but were also associated with greater user satisfaction and perseverance through quit attempts.

Participants expressed an interest in incentive-CM, where verified abstinence is rewarded with tangible or virtual incentives. CM has demonstrated preliminary efficacy in vaping cessation [54,55], with Raiff et al [55] finding that all 8 participants in their trial achieved full vaping abstinence over 2 weeks using a CM-based intervention. CM is often limited by its resource-intensive requirements; however, using nonfinancial incentives, such as in-app rewards, badges, progress milestones, or vouchers, could make it more scalable and accessible. 55 Bridging this concept with theme 4 and AR's immersive and interactive nature, integrating CM within an AR-based vaping cessation app could enhance these effects even further by making rewards feel more tangible and tied to user behavior [22]. For example, virtual rewards could be visually displayed within an AR environment, allowing users to physically interact with their progress or "level up" within a gamified cessation journey. The ability to merge behavioral reinforcement with real-time, immersive feedback in AR could create a stronger sense of achievement and motivation, potentially leading to greater adherence, long-term success, and increased sustainability compared to traditional CM approaches.

Participants highlighted the importance of education and real-time coping strategies, viewing AR as a useful tool for health visualization, as discussed in the fourth theme. Many expressed an interest in tracking their lung recovery over time, seeing improvements as a motivational reinforcement for staying vape-free. However, participants cautioned against overly graphic or fear-based messaging, favoring positively framed reinforcement. When AR-CET was introduced as a potential feature, participants expressed strong hesitancy, fearing that intentional exposure to vaping cues would intensify cravings rather than reduce them. CET may still be a valuble tool for vaping cessation, however further exploration is needed and should be approached with sensitivity. Instead, participants preferred AR-based tools that help identify personal triggers and provide real-time coping strategies, reinforcing the need for interventions that offer behavioral guidance alongside educational components.

Overall, this study is the first to explore youth and young adults' perspectives on AR for vaping cessation, offering valuable insights into the challenges, barriers, and opportunities this population faces. The findings suggest that AR-based tools have the potential to enhance vaping cessation interventions by offering a dynamic, interactive, and user-driven experience. Beyond personalization and engagement, resilience-building and long-term support must be central to intervention design. Regular check-ins through apps or chatbots can provide ongoing support, ensuring users remain connected to their cessation goals even after initial success. By aligning with youth and young adults' digital behaviors and preferences, AR-based tools can bridge the gap between self-directed quitting and structured support, ultimately making vaping cessation more engaging, accessible, and sustainable. Unlike traditional cessation programs, which often emphasize abstinence and will power, AR-based interventions can offer adaptive, personalized support, positioning them as an innovative and effective tool in the evolving landscape of vaping cessation among youth and young adults.

Limitations and Future Research

This study offers valuable insights into youth and young adults' perspectives on vaping cessation and the potential role of AR-based interventions; however, several limitations should be acknowledged. The sample size was appropriate for the study's exploratory and qualitative nature, as ID prioritizes depth and applicability over broad generalizability [31,32]. While the findings provide valuable insights into youth and young adults' vaping cessation experiences, they reflect a specific group of participants, so they may not encompass the full spectrum of cessation behaviors across diverse populations. The inclusion criteria encompassed youth and young adult participants aged 16 - 24 years; however, only 2 participants were 19 years old or younger, thus limiting the study's capacity to capture the experiences of younger youth. While diverse in gender and vaping experiences, the findings may not fully capture the perspectives of harder-to-reach populations, such as individuals who have never attempted cessation, those from lower socioeconomic backgrounds, or those with limited access to digital technologies. Future research should investigate the barriers to engagement with digital cessation tools among underrepresented groups to ensure that interventions are inclusive and accessible. The small, exploratory sample held limited information power, particularly regarding gender-based differences. As Donaldson et al [56] noted, gender and sexual minority groups are at higher risk for vaping but remain underrepresented in cessation research. By incorporating gender as a disaggregating construct, this study emphasized its importance in understanding vaping cessation. Future research using mixed methods approaches or larger samples could better capture gender-specific influences, ensuring interventions are inclusive and responsive to diverse needs. Including a wider range of demographics and vaping histories in future studies could further refine and expand the applicability of these findings, ensuring that intervention recommendations are responsive to the varied needs and contexts of those attempting to quit vaping.

Second, the study relied on self-reported experiences, which may be subject to recall bias or social desirability effects. While qualitative methods provide rich, in-depth insights, future studies could incorporate longitudinal designs to track how youth and young adults' experiences and cessation strategies evolve over time, particularly in response to real-world engagement with AR-based interventions. Additionally, experimental or mixed methods approaches could complement qualitative findings by quantifying the effectiveness of specific AR features, such as gamification and AI-driven support.

Third, a key limitation of this study is the theoretical nature of AR discussions, which inherently limits the study's alignment

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with ID. ID is intended to generate applied health knowledge that informs real-world practice; however, this study's exploration of AR as a cessation tool was largely hypothetical, as participants did not interact with a tangible AR-based vaping intervention. Without direct engagement, participants' perspectives were based on speculation rather than lived experience, limiting the extent to which findings can be directly translated into applied interventions. This limitation was mitigated by encouraging participants to interact with popular AR-based apps (eg, Pokémon Go) prior to the sessions to help foster a preliminary understanding of AR technology and its potential applications. Future research should prioritize pilot testing AR-based vaping cessation tools, allowing for direct user interaction and real-world evaluation of features such as gamification, behavioral tracking, and AI-driven support. AR interventions should be designed to foster both intrinsic and extrinsic motivation, leveraging personalized and adaptive mechanics to enhance user experience and adherence.

Conducting studies where participants actively engage with AR-based cessation apps would enhance the credibility and transferability of findings within an ID framework by grounding insights in actual user experience rather than hypothetical feedback. Further exploration of advanced features, such as AI-driven personalization coupled with AR, could enhance the adaptability of interventions by tailoring support based on users' behaviors, progress, and engagement patterns. AI could provide immediate feedback and personalized cessation plans, reinforcing motivation and commitment while reducing the burden on health care professionals [57]. Additionally, given the increasing prevalence of dual substance use, future interventions should address the co-occurrence of vaping and cannabis use, recognizing that these behaviors often intersect and present unique cessation challenges [58]. Lastly, while this study focused on youth and young adults' perspectives, future research should explore collaboration among end users, health care providers, digital health developers, and public health stakeholders to ensure that AR-based vaping cessation tools are evidence-based, youth-friendly, and effectively integrated into existing cessation frameworks.

Conclusion

In conclusion, this study is the first to explore youth and young adults' perspectives on AR for vaping cessation, offering new insights into how digital interventions can be designed to meet the evolving needs of young people. As vaping remains a pressing public health issue, particularly among youth and young adults, there is an urgent need for innovative, evidence-based interventions that move beyond traditional cessation approaches. By leveraging personalization, interactivity, and immersive technology, AR app-based tools have the potential to redefine vaping cessation support, making it more engaging, accessible, and effective. Building on this work, future research should focus on designing and pilot-testing AR interventions, including mixed methods work that evaluates real-world engagement and effectiveness. By combining co-designed elements, tailored features, and evidence-based strategies, digital interventions can empower youth and young adults to not only quit vaping but also sustain long-term behavior change and improve overall well-being.

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Data Availability

To protect the identity of the participants, the raw datasets and transcripts are not publicly available.

Authors' Contributions

Conceptualization: KF, LS, EK, and MKH
Data curation: KF, LS, EK, and MKH
Formal analysis: KF and LS
Investigation: KF and LS
Methodology: KF, LS, EK, and MKH
Supervision: LS, EK, and MKH
Writing—original draft: KF and LS
Writing—review and editing: KF, LS, EK, and MKH

Conflicts of Interest

None declared.

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Multimedia Appendix 1
Qualtrics screener and survey.
[PDF File, 131 KB - xr_v2i1e79674_app1.pdf]

Multimedia Appendix 2
Semistructured interview guide.
[DOCX File, 30 KB - xr_v2i1e79674_app2.docx]

Multimedia Appendix 3
Zoom-based whiteboard activity.
[DOCX File, 1300 KB - xr_v2i1e79674_app3.docx]

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Abbreviations

AI: artificial intelligence
AR: augmented reality
BCT: behavior change technique
CET: cue exposure therapy
CM: contingency management
ID: interpretive description
RTA: reflexive thematic analysis

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Development and User Experiences of a Novel Virtual Reality Task for Poststroke Visuospatial Neglect: Exploratory Case Study

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Abstract

Background: Visuospatial neglect (VSN) affects spatial awareness, leading to functional and motor challenges. This case study explores virtual reality (VR) as a potential complementary tool for VSN rehabilitation.

Objective: Specifically, we aim to explore the initial experiences of patients and physiotherapists engaging with a novel protocol, using an audiovisual cue task to support VSN rehabilitation.

Methods: A preliminary VR task integrating audiovisual cues was co-designed with 2 physiotherapists. The task was then tested with 2 patients with VSN over 12 sessions. The intervention focused on engaging neglected spatial areas, with physiotherapists adapting the task to individual needs and monitoring responses.

Results: Initial testing with 2 trainee physiotherapists indicated high usability, engagement, and perceived safety. Two patients with VSN completed 12 VR sessions. For Patient A, completion times increased following the introduction of an audio cue, though modeling indicated a nonsignificant linear trend (β=0.08; P=.33) and a marginally significant downward curvature (β=−0.001; P=.08). In contrast, Patient B showed a significant linear decrease in completion times (β=−0.53; P=.009), with a quadratic trend indicating a performance minimum around session 10 (β=0.007; P=.04). Intraweek variability also decreased. Motor scores (Box and Block Test and 9-Hole Peg Test) remained stable, and subjective feedback indicated improved mobility confidence and positive task engagement.

Conclusions: Further research with larger cohorts is needed to confirm the VR task's utility and refine the intervention.

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KEYWORDS

virtual reality; visuospatial neglect; physiotherapy training; audiovisual cues; patient experience; case report

Introduction

Background

Following a stroke, approximately 30% of stroke survivors experience neglect [1]. Neglect is a neurological disorder that poses significant challenges for rehabilitating behavioral deficits, including motor functions and perceptual-cognitive impairments, such as spatial awareness. Among the various types of neglect, visuospatial neglect (VSN) stands out as a specific subset. This is characterized by a failure to attend to objects or events within a defined region of the visual field, commonly affecting the left side [2]. These deficits increase the risk of falling and contribute to caregiver burden [3]. Conventional rehabilitative interventions typically involve manual interactions between patients and therapists, which can be physically demanding for practitioners and patients, leading to disempowerment, boredom, and reduced motivation when activities lack autonomy or engagement [4].

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The integration of technology-based modalities, such as serious games and virtual reality (VR), with conventional rehabilitative interventions has emerged as a promising approach to engage patients with poststroke neglect [5]. When used in conjunction with traditional rehabilitation, including physiotherapy interventions, these modalities offer the potential for a more motivating treatment experience. Despite the potential benefits of these approaches, the use of audiovisual cues within VR adjunctively with physiotherapy remains poorly understood in terms of the subjective experience of patients with VSN. Consequently, the objectives of this case study are (1) to develop a real-time VR-based physiotherapy training solution tailored for individuals with VSN and (2) explore how audiovisual cues may influence the performance and rehabilitation experience of physiotherapists and individuals living with VSN during interaction with the VR-based training solution across 12 sessions.

Visuospatial Neglect

VSN, a common cognitive deficit following a stroke, is characterized by persistent spatial inattention, often manifesting unilaterally [2,6]. Patients with VSN struggle to acknowledge or respond to visual stimuli presented on the side opposite to the damaged hemisphere, often behaving as if that side of their visual field does not exist [7,8].

VSN is typically associated with damage to the posterior-parietal cortex of the right hemisphere. However, recent lesion mapping studies suggest a high degree of variability regarding the anatomical basis for neglect [9] with the temporo-parietal cortex, frontal cortex [10], occipital cortex [11], cerebellum [12-14], and even subcortical regions [15] have been linked to neglect. Furthermore, it has been associated with disconnections in white matter tracts, such as the superior longitudinal, inferior longitudinal, and inferior fronto-occipital fasciculi [9]. These varied findings highlight the complexity of VSN's neuroanatomical correlates.

Neglect mainly affects higher-level spatial processing modalities, such as visual and auditory spatial processing [16]. However, the empirical relationship between visual and auditory tasks with neglect remains unclear [8]. As studies have simulated multisensory (typically audiovisual and tactile) training procedures, improvements have been observed after training that used temporally congruent audiovisual input [16,17]. Therefore, the exploration of multisensory and specifically audiovisual training procedures is warranted.

Physiotherapy and Patient-Centered Treatment

Poststroke rehabilitation programs commonly feature physiotherapy to address motor and sensory impairments [18]. Physiotherapy is a vital primary care service within formal health care systems, aiming to sustain optimal physical functioning through various nonpharmacological interventions, such as progressive exercises [19,20]. Previous research [21,22] indicates that task-specific repetitive practice is essential for attaining lasting improvements in motor learning and motor function.

Recent trends in physiotherapy further emphasize the importance of patient-centered treatment [23]. Patient-centric physiotherapy treatment involves physiotherapists providing support to empower patients by providing emotional and physical assistance, alleviating fears and anxiety, and involving family and friends in treatment and care plans when possible. Patient-centered support often takes various forms of communication, including both verbal and nonverbal methods, such as tactile interactions and patient education [24]. Given the multifaceted nature of conditions, such as VSN, where multiple aspects of perception and movement may be affected, patient-centered support is particularly pertinent, as it addresses a wide range of dimensions in the recovery process.

Since the reaching and grasping skills of these patients are often limited, physiotherapy programs targeted for poststroke neglect rehabilitation include grasping training. Grasping training for poststroke neglect aims to improve spatial representation ability, as well as an enhancement in reaching, interacting, and grasping skills toward the neglected area or environment [25]. This often takes the form of congruent visual scanning training and motor rehabilitation tasks [26,27]. Studies suggest grasping training using methods such as home-based programs and custom-developed VR simulations is beneficial for patients with poststroke neglect to develop reaching and grasping skills that can be tailored to individual needs [28], which improves their ability to grasp objects [29-31].

VR and Neglect Rehabilitation

VR has emerged as a promising technology to be used adjunctly with physiotherapy, aiming to influence physical behaviors and movements within immersive, computer-generated environments. Sensory-motor tasks in VR offer several distinct advantages for physiotherapists. VR provides a safe setting for patients to engage in realistic and repetitive movements, either as an adjunct to conventional physiotherapy or in tandem with it, under the real-time supervision of therapists [5]. Evidence from various studies suggests that VR can improve the frequency of motor tasks in poststroke rehabilitation by increasing practice intensity [32], improving hand function [33], and promoting neuroplastic changes [34].

Recent studies have demonstrated VR's effectiveness in various stages of VSN management, ranging from diagnosis [35] and assessment [36] to motivation and rehabilitation [37]. This is in part due to VR's capacity to create immersive and controllable training environments, enhancing patient engagement and motivation, potentially leading to better treatment adherence and outcomes [38]. For rehabilitation, several studies have used VR to simulate realistic grasping training through hand grasp motions, showing promising results [39,40]. The engaging, adaptable, and measurable aspects of VR thus prove it to be a promising tool for VSN rehabilitation.

VR and Audio-Tactile Cueing in Neglect Rehabilitation

In VSN rehabilitation, audio-tactile cues enhance the immersive effects of VR by directing attention toward the neglected space through multimodal sensory engagement, thereby promoting orientation and visual awareness on the affected side. Studies by Knobel et al [41] and Leitner and Hawelka [42] provide evidence that audio-tactile cueing in VR settings with patients with VSN can effectively improve patients' attentional

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orientation and head movement toward stimuli, assisting them to overcome rightward orientation biases. VR interventions can provide a structured and repeatable therapeutic experience, aligning with neuropsychological approaches (eg, prism adaptation therapy, a rehabilitation technique involving the use of prism glasses to shift the visual field and correct for visual displacement). Prism adaptation therapy has been integrated into VR environments, leading to more effective rehabilitation outcomes [43] as well as visual scanning training [42,44]. Phasic alertness (the brief adaptive increase in arousal that occurs in anticipation of an upcoming warning stimulus, see eg given by Posner [45]) has also been shown to be positively influenced with audiovisual cueing, leading to improvements in the balance of visual attention in patients with neglect [46]. Auditory cues can trigger fast, automatic shifts in spatial attention, suggesting preservation of strong links between auditory and visual attention mechanisms in patients with neglect. Sustained long-term improvements have been found following intensive and prolonged multisensory audiovisual stimulation [47].

This case study addresses a critical gap in the co-design and iterative development of VR-based interventions tailored specifically for hand grasping training in patients with VSN. Unlike generalized VR applications in rehabilitation, this intervention was designed through interdisciplinary collaboration with physiotherapists to integrate audiovisual cueing within a hand-grasping task, offering a novel approach to VSN rehabilitation [48]. For instance, existing VR-based interventions [49] have primarily focused on perceptual training through visual scanning tasks or general attentional cueing, whereas the system developed here aims to incorporate elements of compensatory motor initiation, less commonly addressed in this context. Compensatory motor initiation refers to the use of alternative motor strategies, such as gaze shifts, to facilitate movement toward the neglected hemispace, particularly in patients with VSN who exhibit impaired initiation on the contralesional side [50]. Accordingly, this VR intervention distinctly explores the integration of physiotherapist-informed design components, such as adjustable audiovisual cueing and targeted hand-grasping tasks, to address compensatory motor initiation and spatial attention. The structured co-design process included iterative testing and refinement to align the intervention with patient-specific needs and therapeutic goals [51]. In addition, exploring how such tasks influence individual patient experiences over multiple sessions provides valuable insights for personalizing rehabilitation strategies, addressing a critical need for evidence in this domain [1,52]. Furthermore, understanding how such a task influences the experience of individual patients over a series of physiotherapy sessions is unknown. Therefore, the following research question directed the study:

RQ. What are the initial experiences of patients and physiotherapists using a custom-developed VR-based hand grasping training protocol?

Accordingly, the aims of this study were 2-fold: (1) to develop a solution using audiovisual cueing to be used during real-time physiotherapy training and (2) explore the initial experiences and perceptions of patients and physiotherapists regarding the use of audiovisual cueing in the VR task.

Methods

Intervention Development

The case study presents a VR-based physiotherapy intervention designed for hand grasping training in the rehabilitation of VSN. This intervention uses VR to produce customizable visual and audio cues in its environment, aiming to address the requirements of individual patients with VSN. For instance, elements such as the timing, location, and dynamics of these cues can be adjusted to optimize the patient's training experience. In this intervention, participants engage in a VR task. The VR task is a single trial where a ball, serving as the visual cue, appears to the left within the VR environment, preceded by an audio cue to signal its location. The ball bounces in a fixed vertical up-down trajectory. This allowed users to plan their motor responses, such as grasping. Participants were tasked with grasping the ball as quickly as possible and were limited to grasping 1 ball per trial. In this study, we first focused on usability, followed by user testing. Audio cues were introduced in the seventh week to streamline the complexity of the VR task. This procedure-based approach to VR intervention design involves a structured process of usability testing and the phased introduction of multisensory cues to enhance task performance, aligning with principles of effective VR rehabilitation training [48].

Aligned with the UK Medical Research Council's (MRC) guidelines for developing complex interventions [51,53], this case study emphasizes a structured and evidence-based approach to intervention development. The UK MRC's emphasis on exploring feasibility and acceptability in the early stages of intervention development was addressed through detailed user testing (by both physiotherapists and patients with VSN) and design, to refine the VR task and ensure it met necessary user requirements.

Design and Implementation

For the purposes of this case study, an experimental VR environment was developed in Unity3D (Unity Software Inc). As shown in Figure 1, the VR environment contained multiple objects. Using Unity3D, the software developer crafted an experimental VR environment that featured a prominent visual cue in the form of a red ball. In addition, an auditory directional cue was used. The audio cue directed the user to the ball's location, and the task was considered accomplished upon successfully grasping the ball.

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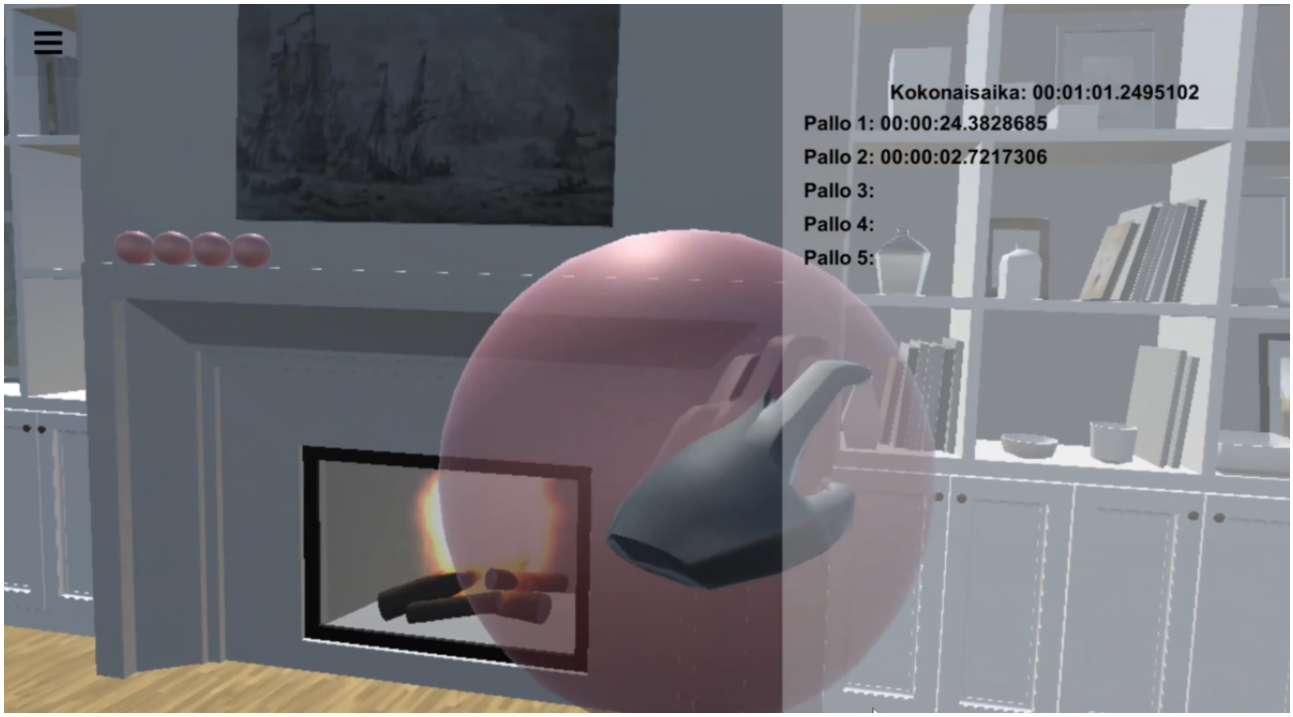
Figure 1. First-person perspective of the virtual reality task environment.



Directional Cue Design

Visual Cue

Figure 1 illustrates a red ball designated as the focal point for participant interaction, serving as a visual cue to direct their attention toward the task of grasping during trial runs. The figure depicts a VR task environment as viewed from a first-person perspective. In the center of the room, a red ball serves as the primary visual cue. The user's left hand is shown reaching for the red ball, indicating the action-based element of the task. The ball appears in the center, as this was captured during early development and captured only for example purposes. The interface also includes a timer display with labels in the Finnish language, such as "kokonaisaika," meaning "total time," and "Pallo 1" through "Pallo 5," meaning "ball 1" through "ball 5," respectively. These labels are followed by time stamps, revealing the duration taken to interact with each ball; for instance, "Pallo 1" took 24.38 seconds, and "Pallo 2" took 2.72 seconds. The sequence suggests that the user will engage with a series of 5 such balls throughout the exercise. The surrounding environment is minimally designed with a neutral color palette, emphasizing focus on the task elements. The Unity 3D rendered scene of the VR environment is presented in Figure S1 of the Multimedia Appendix 1

Developed using Unity 3D, the designated grasping zone is active from the ball's periphery to its center and is detected by Unity's collision system. The ball is designed to move vertically within the space (ie, vertical cues have been found to influence spatial orientation and potentially aid in rehabilitation of patients with VSN, see Lafitte et al [54]). The dynamics of this movement, such as the bounce speed, can be adjusted from 1 millisecond to 60 seconds through the application settings.

For this cue, a range of available adjustments was deemed important, as Golay [55] suggests that the effectiveness of cues in neglect rehabilitation can vary depending on the interval between the cue and the target. The starting position of the red ball correlates with the user's spatial location in the VR environment, which is determined by the positioning of their head-mounted display (HMD). The ball ceases movement when the participant's hand is near, simulating interaction. Successful grasping is indicated by the ball's disappearance. The appearance of the ball is designed to occur within the participant's left visual field (based on the [56] reach task consistently using targets appearing outside a central fixation point), determined by the spatial audio cues' effect on the participant's orientation in the HMD. The red ball appears approximately 61 centimeters (2 feet) from the participant, facilitating reach and interaction (eg, [57]).

Audio Cue

The audio cue was made by using the spatial sound capabilities of Unity3D 5.3, with the spatial blend parameter set to full 3D, allowing for precise auditory localization in conjunction with visual elements. Unity's spatial audio geometrically simulates sound sources within the environment, with the auditory cues emanating from the expected ball appearance location relative to the user's HMD position, facilitated by a head-related transfer function (HRTF) system. HRTF technology mimics how sound is affected by the listener's head and ears, providing a naturalistic sound perception based on directionality. The audio cue lasted 2.61 seconds and served to alert users to the specific location where visual stimuli would appear. This was based on prior research by Yoshizawa et al [58] demonstrating that a cue lasting 2 - 3 seconds effectively directed attention toward the neglected side during VR rehabilitation tasks for patients with hemispatial neglect. Studies by Dozio et al [59] and Knobel et al [41] suggest that short-duration audio cues are both beneficial and suitable in VR interventions for VSN rehabilitation. An interstimulus interval of 105 milliseconds between the auditory

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and subsequent visual cue was optimized to prepare the patients for grasping the red ball (visual cue). The frequency spectrum of the auditory cue showed a prominent peak at approximately 500 Hz (≈ −30 dB) within the 50–20,000 Hz range, with additional smaller peaks across the low-frequency range. Figure 2 illustrates the frequency spectrum of the auditory cue. Figure 3 provides a 3D visualization of the auditory cue.

Figure 2. Frequency spectrum plot of auditory cue.

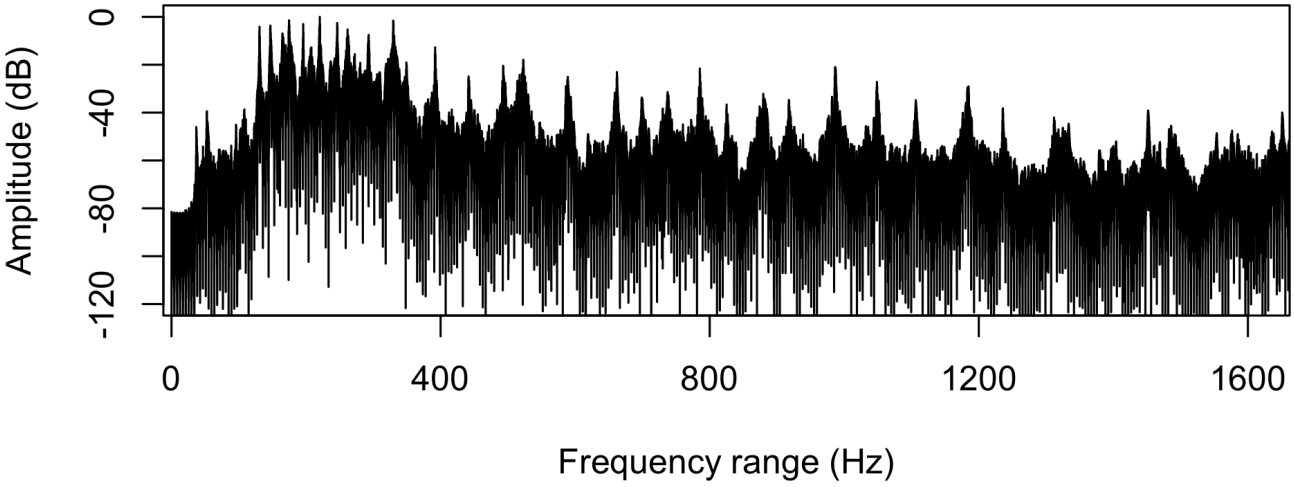

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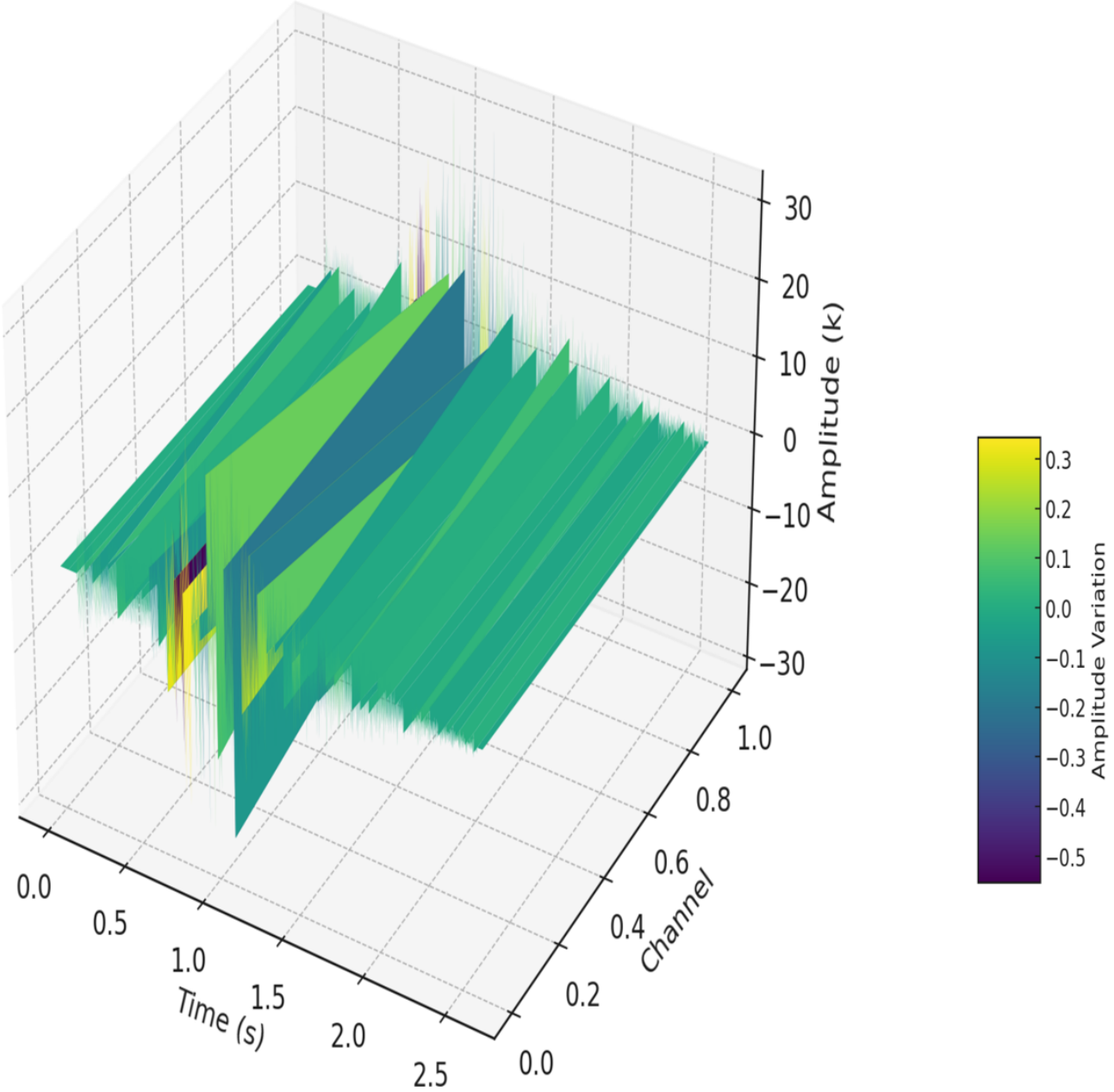
Figure 3. 3D visualization of auditory cue. The x-axis—Time (s)—denotes time in seconds, the y-axis—Channel—displays the left and right audio channels, and the z-axis—Amplitude (k)—illustrates the amplitude scaled in kilounits. The color gradient, as indicated by the color bar labeled "Amplitude Variation," visually depicts the amplitude fluctuations within the auditory cue.



Task Parameters and Environment Design

VR Task Description

The VR task includes 1 trial with a ball appearing to the left (15° to the left), within a 30° horizontal plane and a 50° vertical plane within the limits of the VR room. To complete each trial, participants are required to successfully grasp the floating ball as fast as possible (includes a 5-minute time-out period for managing patient fatigue, [22,23,60]). Upon appearing, the ball bounces with a vertical up-down trajectory in the room and stays bouncing within a fixed vertical trajectory until the participant grasps the ball. Participants were limited to grasping 1 ball once per trial. To initiate the appearance of a new ball, participants were required to rotate their trunk and direct their gaze toward the center point of the field of view (FOV). This central gaze point was represented in the VR software as a painting positioned above a fireplace object. The process was marked by a countdown timer, starting from 3 and concluding at 0, at which point a new ball was generated. The duration of each trial was measured (in ms) until a successful grasp occurred. The ball's visual stimuli were depicted through its appearance in the VR environment. An audio cue of where the ball will appear across the 30° horizontal plane was activated prior to the ball appearing to alert the patient to the appearance location (interstimulus interval between the audio cue and visual cue=105 ms, ie, [41]). There were 15 trials in each location across the 30° x 50° degree plane. The timer's data aimed to provide insights into how target grasping efficiency is affected by the size and distance of objects. In addition, multiple trials were incorporated and the elimination of manual restarts to improve the interaction process and reduce the cognitive load associated with initiating new trials. Data output was presented

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in the form of a text file, which recorded participant response times for each trial, audio cue sounds, and trial dates.

Task Development Aims

The development of this VR task is specifically tailored for inclusion in poststroke physiotherapy rehabilitation, building upon the Reach Task conceptualized by Mattingley et al [56]. The original task involved participants reaching toward a stimulus at the edge of their visual field. Our adaptation for VR purposes follows this principle, focusing on the neglected visual field to help distinguish perceptual deficits from motor control difficulties.

To support physiotherapeutic goals, the task encourages the use of compensatory strategies—alternative motor patterns developed to adjust for lost function, as described by Levin et al [61]. Patients with VSN engaging in these motor patterns is critical for fostering attentional shifts [62]. Integrating audio cues with visual targets is designed to enhance anticipatory behavior [55], supporting patients with neglect to proactively direct their attention and gaze toward the task at hand.

Applying Fitts Law as a Guiding Principle for Task Difficulty

Fitts law is a psychological principle stating that the difficulty of a perceptual-motor task, such as pointing or selecting targets, is a function of target size and distance [63]. The smaller the target size, the slower and more difficult it is for individuals to accurately reach or activate the target. This provided a framework for reducing the difficulty by enlarging the target and thereby increasing the accessibility of user interactions within the VR environment. As part of subsequent development tasks, the software developer adjusted the FOV to 30° on the horizontal plane and 50° on the vertical plane using Unity's built-in parameters. This adjustment was chosen to reduce the distance to targets, thereby making the task more accessible for patients with VSN to successfully grasp objects (this also reduced the potential for cybersickness effects, eg, [60]). The adjustment of the FOV to specific angles on the horizontal and vertical planes is also made in relation to the effective size and position of the targets (ie, the balls) within the VR environment (see Figure 4 depicting a conceptual diagram representing the appearance location for the primary visual cue within the updated FOV parameters). The ball was set to appear at ground level, ascend vertically to the ceiling, and descend vertically back to its initial point of origin on the ground (up-down trajectory).

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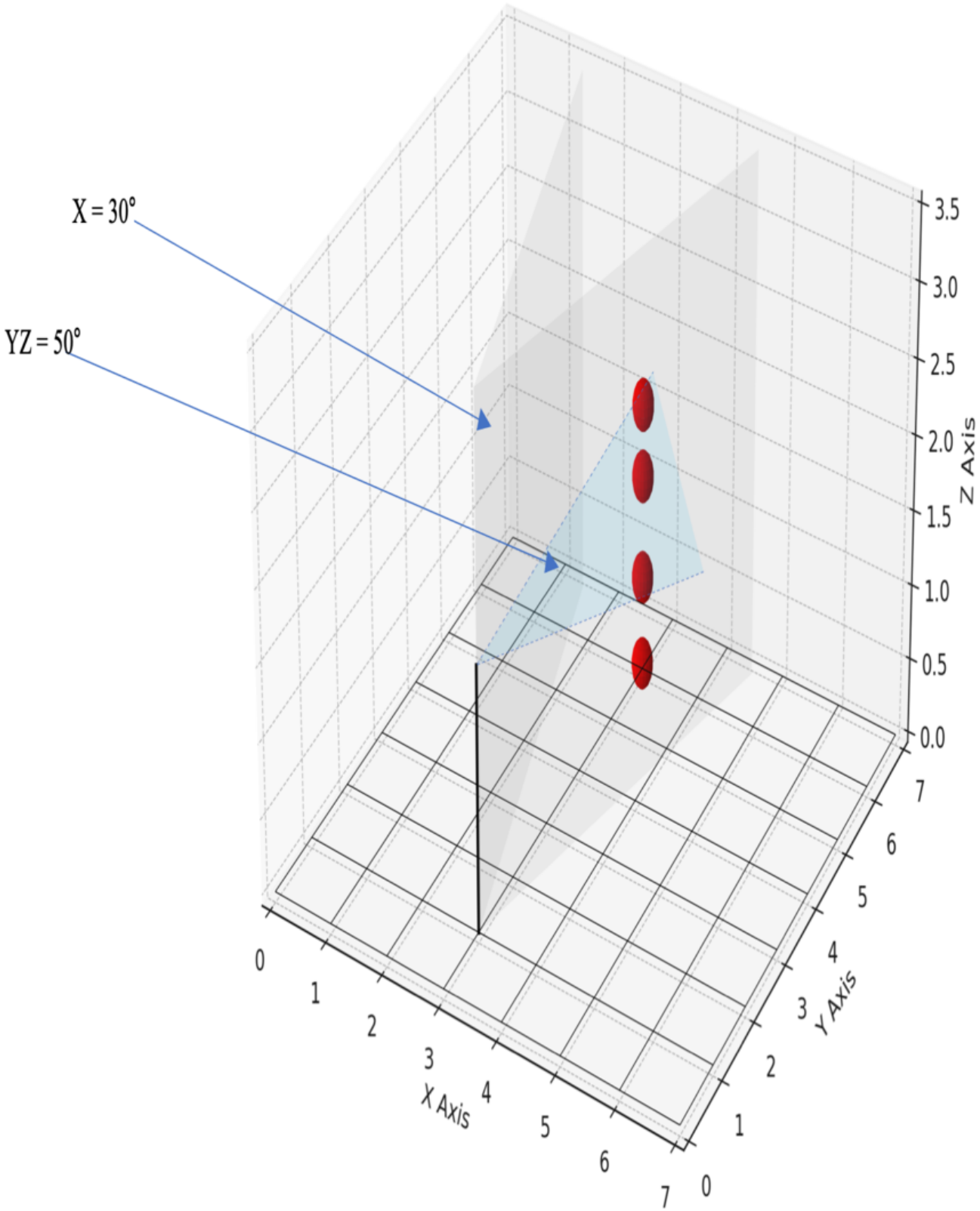
Figure 4. Illustrative figure depicting the field of view in the virtual reality task. This figure depicts the field of view in the virtual reality task, with 4 red spheres indicating potential appearance locations of the primary visual cue within a 15° range to the left of the central gaze. The black line represents the participant's position at coordinates x=3, y=1. “X=30°” and “YZ=50°” denote the maximum horizontal and vertical area visible to the participant. The 2 blue arrows indicate the breadth and height of the participant's potential visual engagement area during the activity. The diagram is conceptual and not drawn to scale; axis measurements of 7x7 meters (X and Y) and 3.5 meters (Z) are for reference only.



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High Tech Computer Corporation Vive Head Mounted Display

The VR intervention was delivered using the High Tech Computer Corporation (HTC) Vive HMD, a tethered head-mounted display equipped with lighthouse tracking technology for accurate room-scale motion capture. Its compatibility with HRTF audio makes it suitable for delivering spatial audio cues, essential for the task design. A detailed specification of the VR hardware setup, including display resolution, connectivity, and audio components, is provided as supplementary information (Section A in Multimedia Appendix 1).

Leap Motion Controller

Hand tracking in the VR task was achieved using the Leap Motion Controller, a touchless optical tracking device that allows real-time monitoring of hand and finger movements [64]. This interface enabled intuitive grasping interactions without the need for handheld controllers. Haptic feedback was not included, in line with previous studies highlighting the complexity it introduces in poststroke rehabilitation tasks [64,65]. A specification of the Leap Motion Controller and how it pertains to this study is provided as supplementary information (Section B in Multimedia Appendix 1).

Usability and Preliminary Testing

Preliminary User Testing

During the initial development phase, collaboration took place between a physiotherapist from the anonymous physiotherapy clinic, who played the role of a user tester, and a software developer from (anonymous organization). For testing purposes, they used a PC-based system along with a tethered HTC Vive HMD and a Leap Motion Controller. Initially, challenges emerged related to latency, particularly concerning the responsiveness of the Leap Motion Controller device to the grasping gesture. To overcome this issue, they decided to externally mount the Leap Motion Controller on the HMD to enhance the tracking of hand movements and gestures, serving as a trigger point for task completion. Mounting Leap Motion Controllers on a VR HMD has been found to enlarge the tracking area for hand tracking in VR software programs, thereby improving user experience with enhanced hand and gesture tracking [66].

Usability Assessment

To assess usability as well as the physiotherapists' perception of the task and system, 4 questions from the Technology Acceptance Model questionnaire [67], 2 questions from the Engagement in In-Game Questionnaire [68] and 1 question from the Safety Attitudes Questionnaire [69] were adapted and used for a usability assessment. The questions were answered using a 5-point Likert scale, ranging from "fully disagree" to "fully agree" (see Table S1 in Multimedia Appendix 1).

Ethical Considerations

The study was conducted in accordance with the Declaration of Helsinki [70] and a favorable ethical statement from the Pirkanmaa Ethics Committee (984/2021). Written informed consent was obtained from all participants. Personal data were processed under a Data Processing Agreement in compliance with the GDPR (EU, 2016/679). Data were pseudonymized, stored securely on password-protected servers, and accessible only to authorized researchers. No identifiable images or personal identifiers are included. Participants were reimbursed for travel expenses but received no other compensation.

Results

Feasibility and Usability Feedback (Physiotherapists)

Before conducting tests with participants with VSN, 2 trainee physiotherapists from an anonymous physiotherapy clinic participated in VR task test sessions to gain insights into their experiences with the technology. Subsequently, these test sessions were immediately followed by a survey where the 2 physiotherapists provided feedback regarding their subjective experiences with the VR task. The survey was administered using Webropol (Webropol Oy) software. Each trainee used the application for approximately 10 - 15 minutes before completing the survey. Table 1 aimed at assessing (1) the physiotherapists' perceived ease of use of the system, (2) the physiotherapists' engagement while using the system, and (3) their perception of the safety of the VR task. The questions for usability (Question 1–Question 4), task engagement (Question 5), and safety (Question 7) were rated highly by both trainee physiotherapists. The question associated with difficulties in learning the task (Question 6) was rated low.

Table . Questionnaire results from 2 trainee physiotherapists.

Survey question	Physiotherapist 1 rating	Physiotherapist 2 rating
I think the system is easy to use	4	4
Learning to use the system is not a problem	4	5
I enjoyed using the system	4	4
I would like to use the system in the future if I had the opportunity	4	4
Learning to use this VR[a] task was easy	4	4
Was learning the task difficult?	2	2
I would feel safe using this as a patient	4	4

[a]VR: virtual reality.

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Following feedback from the physiotherapists during initial testing, session length was set to approximately 10 - 15 minutes. While fatigue was not directly measured, this duration was selected to support tolerability and aligns with findings recommending shorter VR sessions (10 - 30 min) to reduce fatigue in poststroke rehabilitation [71].

Patient Characteristics and Baseline Function

Patients were recruited between February and March 2022 from inpatients with poststroke neglect referred to care at the anonymous hospital/clinic, Finland. Inclusion criteria required participants to have a right hemisphere stroke with diagnosed neglect, be right-handed, be medically stable, be without hearing impairments, cognitive deficits (eg, learning difficulties), or hemianopia (loss of vision in one-half of the visual field), and be aged 18 years or older. In addition, patients were assessed for their physical and cognitive ability to perform the audiovisual VR task by a physiotherapist team. Patients were excluded if motor or communication impairments, as determined by the physiotherapists, were severe enough to prevent task participation or understanding of instructions. Eligible inpatients received detailed study information, and participation was discussed.

Based on the results of the previous phase of testing, and on the expertise of the physiotherapy clinic, we decided to use the VR task as part of physiotherapy sessions with 2 patients with poststroke neglect for the next phase of exploration. To preserve procedural integrity and ensure personalized care, sessions were conducted by 2 licensed physiotherapists from an anonymous hospital/clinic. Patient A was a 46-year-old male with left-sided hemiparesis and VSN, 1 year poststroke (Barthel Index: 70/100). Patient B, a 37-year-old female with hemiplegia and VSN, was 4 years poststroke (Barthel Index: 95/100). Both were right-handed and met inclusion criteria (full clinical profiles and ADL scores are presented in Table S1 and Section D in Multimedia Appendix 1).

The inclusion of 2 patients with differing clinical profiles, a mild case (Patient A's mild hemiparesis) and a more severe case (Patient B's severe hemiplegia), was a deliberate methodological choice consistent with early-phase intervention research (eg, UK MRC guidelines [51,53]). This heterogeneity enabled an initial assessment of the VR system's usability across a spectrum of functional symptoms and rehabilitation timelines. Such purposive sampling is supported in the development of complex interventions, where the goal is to evaluate feasibility, individual responsiveness, and context-specific implementation [51,53,72]. In neurorehabilitation, evidence shows that early inclusion of diverse patient profiles enhances understanding of task usability, supports iterative design, and informs future personalization strategies [1,41]. Furthermore, diverse case inclusion enables deeper insight into patient-centered customization [17,52] (see eg, [73] where VR task parameters were adapted to patients with varying upper-limb impairments, improving usability, and elevating future patient adherence to the intervention).

Description of Patient Test Sessions

Physiotherapy interactions were standardized across both patients to ensure procedural consistency while supporting individual needs. Both licensed physiotherapists underwent training in the VR task and applied identical task parameters (eg, 1.19 s ball bounce, consistent audio cue use), emphasizing procedural integrity and a patient-centered framework [74]. Patients received uniform instructions and completed preparatory sessions to familiarize themselves with the VR environment. During sessions, physiotherapists monitored performance in real time and provided feedback based on individual motor behavior, such as compensatory strategies (eg, trunk rotation or delayed reaching). Therapists manually initiated each trial using the in-task menu (see Figure S2 in Multimedia Appendix 1). A detailed description of session setup, training, and interaction procedures is included as supplementary information (Section C in Multimedia Appendix 1).

Assessment Measures

During this phase, the assessment measures encompassed the following: time to completion data (with successful grasps serving as indicators of task completion); initial rehabilitation goals set by the physiotherapists and patients prior to commencing the 12 sessions incorporating the VR task (see Textbox 1); an evaluation of goal attainment postcompletion of the 12 sessions involving the VR task; 2 standardized motor function assessments (ie, the Box and Block Test, BBT, which measures gross manual dexterity—number of blocks moved in 60 s—and 9-Hole Peg Test, 9HPT, which assesses fine motor coordination in seconds [75]; see Table 2); and each patient's subjective experience, documented through their comments following the completion of the 12 sessions.

Textbox 1. Textbox 1. Physiotherapy goals for patients A and B as reported by their physiotherapist.

Patient A goals

- Ability to move in an upright position
- Strengthening of leaning on the left side of the body

Patient B goals

- To gain confidence in walking
- Improve balance
- Muscle condition improvement

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Table . Patient A and B's Box and Blocks Test and 9-Hole Peg Test scores.

Patient	Hand	BBT[a,b] Pre (blocks)	BBT Post (blocks)	9HPT[c,d] Pre (s)	9 HPT Post (s)
A	Left	27	27	21.30	22.40
A	Right	51	50	20.84	23.30
B	Left	23	22	20.77	21.50
B	Right	54	54	21.60	21.20

[a]BBT: Box and Blocks Test.

[b]Scores indicate the number of blocks a patient can move over a partition from one compartment to another within 60 seconds, using one hand.

[c]9HPT: Nine-Hole Peg Test.

[d]Scores provide a standardized measure of fine motor dexterity, particularly assessing hand–eye coordination, finger function, and speed of movement during a precision-based task.

Throughout these initial sessions, both physiotherapists guided their patients to begin the task by focusing their visual attention above the fireplace in the VR environment, focusing on the painting object. Once each patient's gaze was visually focused, a countdown timer, counting down from 3 to 0, initiated the appearance of a ball within the FOV. The patients were then instructed to reach out and grasp the ball as it appeared. Upon the patients' successful grasping of the ball and subsequent completion of this first trial, both patients completed an additional 14 trials before the task ended. The physiotherapists would remain present with their patients throughout the entirety of this study to provide additional support or further instructions that might be needed by the patient. This was also due to safety reasons, as both patients interacted with the task while standing upright.

Patient Completion Time Description

We obtained 180 trials per participant. Before proceeding to data inspection, the data were trimmed to remove the worst (ie, slowest) 2 trials for each week. A visual inspection of the task completion times of both patients is presented in Figure 5. Conducting statistical analyses on 2 patients is supported within the framework of case study methodology, which allows for the test of intervention effects on an individual basis [76].

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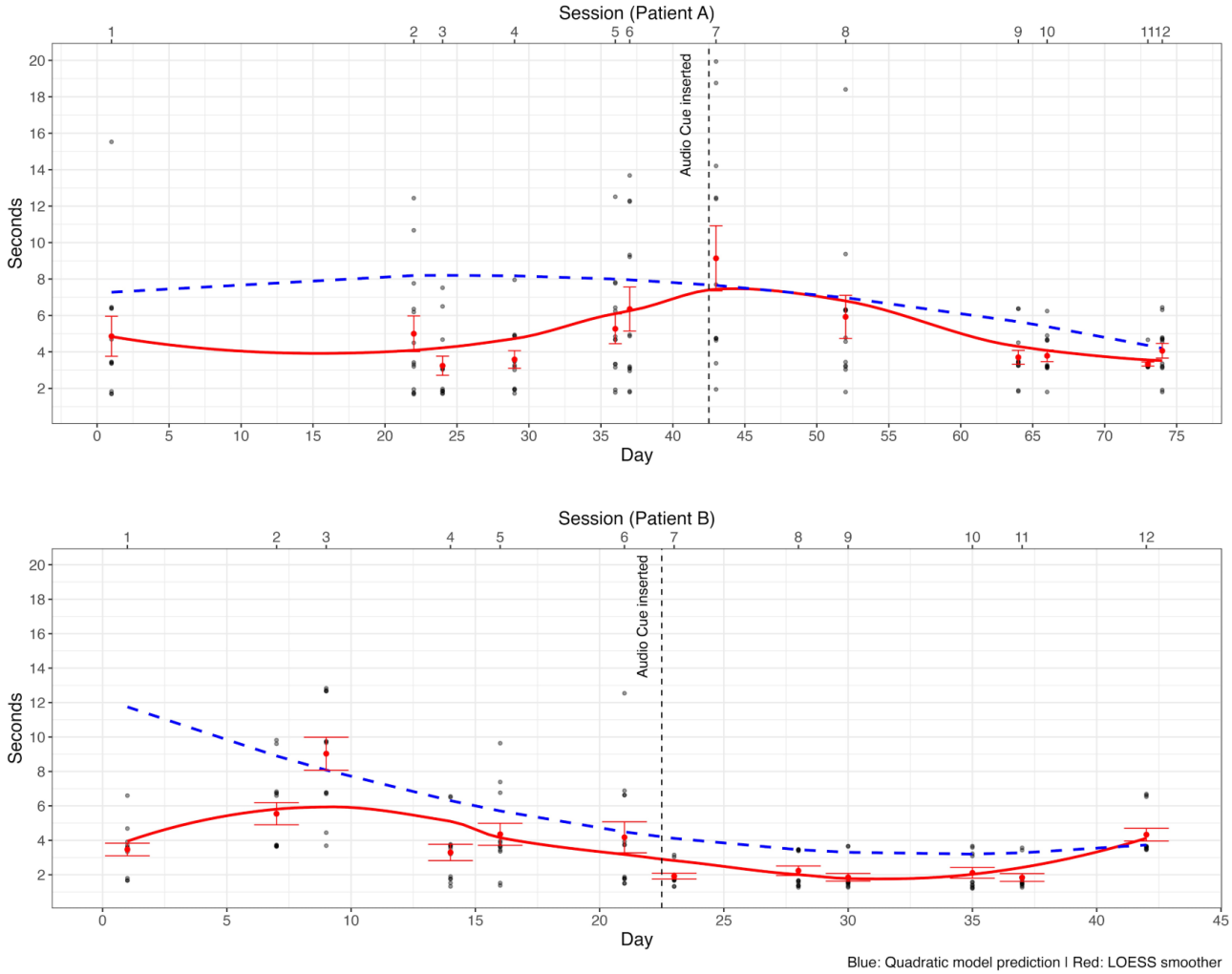
Figure 5. Patient task completion times. Dotted data points illustrate the completion times of each trial. Whiskers denote observed SE of the mean for each day, based on the trial-level data. The solid line signifies a loess interpolation, providing a continuous representation of the completion times over time. The dashed line indicates the trend predicted by the model. To ease visualization, dots above 20 seconds (NA=12; NB=7) are not displayed.



A curve estimation analysis was conducted to examine the trends of the completion times throughout the sessions (N=12 with 15 trials each) for both patients independently. Consistent with the positive skewness of the completion times (Skewness for Patient A=2.63; Skewness for Patient B=4.11), we resorted to a generalized linear model approach through R's *lme4* package [77]. The data were modeled using a gamma distribution, which is ideal for positively skewed strictly positive continuous data [78]. To facilitate interpretation, no link function was used, allowing coefficients to be interpreted directly on the original scale of the outcome. In greater detail, 6 curve models were fitted to the data (ie, linear, logarithmic, quadratic, power, inverse growth, and exponential decay), consistent with methodologies in rehabilitation research that use curve estimation to track patient progress over time [79]. Subsequently, the models were compared based on the Akaike Information Criterion, Bayesian Information Criterion, Nagelkerke R^2, and performance score (through the *performance* R package [80]) (see eg, [81,82] model comparison and information criteria). In all models, the day of the session was used as the predictor. This was preferred over the session number because our sessions were not equally distant in time. For both patients, the quadratic model showed the best fit (see Table 3).

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Table . Model comparison.

Patient and model	AIC[a]	BIC[b]	R^2	Performance
Patient A				
linear	1022	1032	0.070	50.04
quadratic	1019	1032	0.104	100.00
inverse	1031	1041	0.013	0.39
log	1029	1039	0.027	7.63
exp	1031	1041	0.012	0.00
power	1031	1040	0.016	1.96
Patient B				
linear	941	950	0.146	47.02
quadratic	932[c]	945[c]	0.205[c]	85.40[c]
inverse	962	972	0.004	11.09
log	945	954	0.120	28.07
exp	962	972	0.002	14.87
power	957	966	0.042	3.50

[a]AIC: Akaike Information Criterion.

[b]BIC: Bayesian Information Criterion.

[c]Best models.

Regarding Patient A, when inspecting the raw data, a marked increase in completion time was found at session 7, namely, the session wherein the audio cue was added. However, the model suggested that, after a nonsignificant initial increasing trend (β_{linear}=0.08, SE=0.08; *P*=.33), a downward curvature began to emerge, approaching significance ($\beta_{quadratic}$=−0.001, SE=0.001; *P*=.08), around day 24 (ie, session number 3).

Model's results for Patient B indicate that the completion times exhibited characteristics of a significantly decreasing duration (β_{linear}=−0.53, SE=0.20; *P*=.009), where initial task completion times were followed by a gradual deceleration toward a minimum time for task completion, reached around day 35 (ie, session number 10; $\beta_{quadratic}$=0.007, SE=0.003; *P*=.04). Furthermore, Patient B also showed a strong reduction in average completion times and intraweek variability after session 6.

Assessment of Upper Limb Motor Function

The BBT and 9HPT were included as standardized measures of gross and fine motor function, respectively, to assess upper limb performance relevant to the grasping demands of the VR task.

Table 2 summarizes pre- and postintervention scores from the BBT and 9HPT, which were performed under therapist supervision, with patients instructed to direct their focus toward their neglected side. Results show consistent right-hand performance on the BBT while the left (affected) hand showed mild impairment.

Patients' Subjective Experience

At the conclusion of the 12-session period, Patient A and Patient B were individually asked to provide feedback regarding the use of the VR task in conjunction with their physiotherapy treatment (see Table 4 below for a summary of Patient A and B's qualitative feedback). These feedback rounds were conducted by their respective physiotherapists, each posing the same set of two questions: (1) To what extent were you able to achieve your rehabilitation goals? (2) How would you describe your experience with the VR task, using your own words?

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Table . Qualitative feedback from Patients A and B in response to 2 questions posed by their physiotherapist.

Questions	Patient A feedback	Patient B feedback
Were your rehabilitation goals achieved?	"In my opinion, there is no difference in my condition."	"Shifting weight to the left at the end of the period was easier and was slightly more successful. During this period, I started walking without support, without a walking stick." "Walking has become more confident."
How did you experience the VR[a] task (in your own words)?	"The VR task was fun and interesting. The rehabilitation experience was different from my normal physiotherapy experience."	"It felt quite nice and relatively easy. When the balls were on the left *and* behind, it was more difficult. The audio did not seem to really help my performance in the game. But they calmed my thoughts down. The most challenging was when I couldn't move my legs along but, closer to the end it was easier."

[a]VR: virtual reality.

Both physiotherapists transcribed the responses provided by their patients, with the conversations taking place in the Finnish language.

Table 4 indicates that while Patient A did not consciously notice a difference in his condition, he experienced the VR task as fun and interesting. Patient B actively noticed a difference, potentially contributed to by engagement in the VR rehabilitation task. Patient B explained that the VR technique was partially more effective and that shifting weight was easier. In addition, the patient began to walk without support following the VR tasks. Patient B also explained the difficulty in grasping for the ball when it was in the area affected by neglect yet noted that in addition to being a relatively easy exercise, the audio calmed them.

Discussion

Principal Findings

The objectives of this case study were 2-fold: (1) to develop a VR-based solution incorporating audiovisual cueing, designed for real-time use during physiotherapy training sessions for poststroke VSN rehabilitation and (2) to explore the initial experiences and perceptions of both patients and physiotherapists regarding the use of audiovisual cueing within this VR task during rehabilitation. The development process resulted in the successful development of a perceptual motor task customized to meet the needs of real-time physiotherapy applied adjunctly to patients with VSN. Both patients reported a positive subjective experience with the VR training, citing enjoyment and interest, and 1 patient even experienced some improvement in motor function. The VR training was also positively received by physiotherapy trainees. Taken together, these results provide several promising case-specific elements and a potential roadmap for future task development, as well as a larger trial with explicit control and standardization.

Development Aims

The VR task incorporated a progressive approach to rehabilitation [19,20], as evident in the task design. For instance, several adjustments were made in response to user feedback (eg, accessibility considerations were integrated into the system, with a deliberate adjustment of the FOV to cater to patients with VSN). Notably, the usage of VR technology depended on the provision of training to the physiotherapists to use the technology prior to testing it with patients. This training was a vital aspect of the study, ensuring they possessed the necessary expertise to integrate technology into rehabilitation practices safely. Insights from the developer and shared experiences from physiotherapy trainees emphasize the collaborative nature of the approach, incorporating external perspectives and expertise.

Patient A and B Qualitative Feedback

As we used a patient-centered approach, the subjective experience of patients was a key outcome measure. Generally, the qualitative feedback from both patients highlights positive engagement with the task. Both patients reported positively about their experience, stating: "the VR task was fun and interesting" (Patient A) and the VR task was "quite nice" and "relatively easy" (Patient B). The VR task offers a different experience, which was positively received, as Patient A states: "the rehabilitation experience was different from my normal physiotherapy experience." This indicates benefits beyond strictly functional and medical outcomes, such as increased patient engagement during physiotherapy training, which may find alignment with [83].

Patient B's feedback also reflects progress toward achieving rehabilitation goals (eg, the objective of regaining confidence in walking). However, Patient A perceived no significant difference in their condition, which may be due to a multitude of factors. While Patient B also notes some challenges, suggesting potential difficulties related to spatial awareness or balance training, they state that with training, the task did become easier. This may indicate that the VR task was challenging the patient with positive training outcomes as a result. The patient's comment about the game's audio—"it provides a calming effect"—while not intended, aligns with literature on sensory stimulation having a calming effect on patients [84] Though not directly impacting performance, it implies the potential for sensory engagement as a therapeutic aid. However, the functional clarity and perceived usefulness of the audiovisual cues were not explicitly evaluated in this study, pointing to the need for future iterations to include cue-specific assessment. Indeed, as indicated by Danso et al [52], more research must be done to systematically study the impact of sound and music on therapeutic progress. Despite being at distinctly different stages of poststroke recovery and

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presenting with varying symptomatic profiles, both patients reported a positive experience. This outcome highlights the value of customizing the VR task, including directional cues (audio and visual) and in-task settings (eg, background music volume, audio cue volume), to suit individual needs.

The continuous presence of the physiotherapists with their patient throughout the duration of the study, while using VR, suggests a patient-centric approach [24,85]. They actively assisted patients in fitting the HMD as well as manually initiating and monitoring each VR trial, providing real-time guidance and instructions to both patients. The introduction of the VR task to patients by their therapist, coupled with detailed explanations of its objectives and instructions, aligns with the literature on patient-centered education and rehabilitation practice [24]. The aspect of providing the patients with an understanding of the rehabilitation process may have contributed to both patients' positive feedback.

Individual Differences in Task Response

While it is important to keep in mind the anecdotal nature of the evidence due to this being a case study, tentatively positive results were obtained from the patient's interaction with the VR task. The integration of task metrics, standardized motor assessments, and patient feedback highlights individual differences in response to the VR intervention. Patient B showed a significant decay trend in task completion times, along with reduced intrasession variability and subjective reports of improved confidence in walking [17,86]. Patient A, by contrast, exhibited variable completion times and no perceived functional change. Pre- and postintervention scores on the BBT and 9HPT revealed mild left-hand impairment for both patients, with little measurable change over the 12 sessions—suggesting that motor gains alone are unlikely to account for Patient B's improved task efficiency. Notably, both patients performed within normative ranges on the 9HPT [87] for the unaffected hand, with lower scores for the affected hand, consistent with moderate upper-limb asymmetry typical of right hemisphere stroke. Furthermore, across sessions, ball bounce speed (see Table S3 in Multimedia Appendix 1, a proxy for task difficulty) was held constant, indicating that performance differences were not attributable to variation in task demands.

Although the distinct patient profiles, including comorbidities such as VSN, left-side hemiparesis, and left-side hemiplegia, may have influenced task interactions and completion times, it is critical to approach these findings with caution given the case study design. VSN involves attention and awareness deficits with perceptual components [6-8,88], while left-side hemiparesis and hemiplegia relate primarily to motor capacity, with hemiparesis indicating muscle weakness and hemiplegia signifying a complete loss of motor control. In addition, differences in the timing of intervention—Patient A, 1 year poststroke, versus Patient B, 4 years poststroke—may have contributed to variations in task outcomes. Therefore, it is essential to interpret these results as case-specific and within the limitations inherent to a case study framework.

The difference in the total VR task completion times, measured in days for the 2 patients, Patient A (74 days from Day 1 to the final session) and Patient B (42 days over the same period), tentatively suggests a shorter interval between treatment sessions is associated with faster task completion time. This finding is generally supported by the literature [21,22].

Limitations and Future Research

The study has several significant limitations that must be considered case-specific when interpreting its results. A key constraint for the quantitative data is that these are case studies of 2 patients diagnosed with VSN. This limited participant pool, as well as limited characterization of VSN symptoms, is limited by the absence of standardized neglect assessments (eg, the Behavioral Inattention Test) and neuroimaging data (eg, magnetic resonance imaging/computed tomography lesion localization), constraining the interpretation of the underlying neural correlates of task performance in response to this VR task. Furthermore, the 2 patients were at different stages in their rehabilitation journey—one having experienced a stroke in 2018 and the other in 2021. Such disparities in their recovery timelines could introduce confounding variables, thereby impacting the generalizability of the study's findings. In addition, the task-specific outcomes for each patient might have been influenced by numerous uncontrolled variables within the study.

To address these limitations, our future research roadmap involves research including a full sample of patients with VSN (a sample size calculation will be conducted using G*Power software, Heinrich-Heine-Universität Düsseldorf [89], derived from comparable VR rehabilitation studies), as well as additional standardized assessment measures (eg, the Montreal Cognitive Assessment [90], Hospital Anxiety and Depression Scale [91], and Berg Balance Scale [92] will be used). In addition, we will incorporate neglect-specific assessments, such as the Catherine Bergego Scale [93] and Behavioral Inattention Test [94] to quantify changes in VSN. To further investigate the impact of audiovisual cueing, we also plan to incorporate a comparison condition, such as a visual-only cueing group, alongside a standard control group. This will allow us to more rigorously evaluate the specific contribution of multisensory feedback to rehabilitation outcomes.

Regarding the VR task, future analyses of task completion time at varying locations across the 30° horizontal plane will be made to compare how patient progress in reaching easier versus harder targets on the contralesional side. A subsequent study may be designed to include trials on both the left and right sides, incorporating a structured analysis to determine whether the observed improvements in task performance are due to overall speed enhancement or are specifically observed within the neglected hemispace. Although out of scope of this study, collecting richer qualitative reports from family members who regularly interact with each patient will provide clearer insights into the patients' daily activities and recovery needs [3,95], offering a holistic perspective on their progress. While this study did not focus on improvements in grasping skill, methodologies from related research [28,31] could be applied in future studies to assess such skill in patients with VSN using this VR task. In addition, using the Suite for the Assessment of Low-Level Cues on Orientation [96] could enrich our understanding of how patients with VSN perceive and navigate in VR environments, potentially offering valuable insights for rehabilitation practices.

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A follow-up study will include eye-tracking measurements to track visual attention during a trial, as well as include targeted evaluations of audiovisual cue clarity and perceived utility to better understand their functional role in attention orientation and motor engagement (eg, prompting gaze shifts or initiating reach movements). These improvements in study design and data collection will mitigate some of the limitations observed in this study.

Although participants did not report any discomfort or restrictions associated with the HMD equipment, future studies could explore the use of wireless HMD systems, such as the HTC Vive XR Elite, Meta Quest, or Varjo VR, to enhance patient comfort and mobility. In addition, incorporating advanced tracking technology in future studies could improve control over experimental variables.

An additional consideration for future exploration is the potential of the VR intervention to positively influence patient motivation. Both patients in our case studies responded very positively to the VR intervention, and for follow-up studies, measures of patient motivation such as the Motivation in Stroke Patients for Rehabilitation Scale [97] could be included to provide valuable insight into this aspect of the intervention. Crucially, to strengthen the evaluation of patient experience, future studies will incorporate validated instruments, such as the System Usability Scale [67] and Intrinsic Motivation Inventory [98], alongside direct patient-reported outcome measures, to reduce reliance on therapist-transcribed responses and minimize potential reporting bias. Motivation and patient enjoyment have been shown to be important drivers of positive rehabilitation outcomes [5]. The gamified nature of the VR task, coupled with the novelty of the technology, may support patient motivation, encouraging patients to persist in therapy despite the difficulty of the task.

Conclusions

This study explored the development and implementation of a VR-based physiotherapy intervention designed for hand grasping training for VSN rehabilitation. Positive preliminary user experience reports from both patients and physiotherapists provide promising evidence for a future research roadmap of this VR task and highlight the individual patient differences in response to VR-assisted physiotherapy. In addition, the distinct responses of the 2 patients highlight the intervention's potential capacity for personalized adaptation, emphasizing its suitability for diverse VSN rehabilitation needs. To further enhance the feasibility of this VR task in physiotherapy rehabilitation, future research should focus on the use of additional standardized measures applied to a full-scale sample. To better understand the specific impact of this task on attention to the neglected hemispace, future investigations should include a structured analysis of motor performance at varying target locations across the 30° horizontal plane. Furthermore, a full-scale sample could provide further insight into whether observed improvements are due to enhanced movement speed or specific engagement with the neglected hemispace. These findings support the use of VR as a patient-centered tool that can be tailored to individual profiles, offering promising directions for future research in neurorehabilitation.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
Supplementary materials on virtual reality setup and sessions.
[DOCX File, 494 KB - xr_v2i1e72439_app1.docx]

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Abbreviations

9HPT: 9-Hole Peg Test
BBT: Box and Block Test
FOV: field of view
HMD: head-mounted display
HRTF: head-related transfer function
MRC: Medical Research Council
VR: virtual reality
VSN: visuospatial neglect

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Understanding the Views of Health Care Professionals on the Usability and Utility of Virtual Reality Multidisciplinary Team Meetings: Usability and Utility Study

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Abstract

Background: Multidisciplinary team (MDT) meetings are one of the facilitators that enhance knowledge sharing among health care professionals. However, organizing a face-to-face MDT meeting to discuss patient treatment plans can be time-consuming. Virtual reality software is widely used in health care nowadays to save time and protect lives. Therefore, the use of virtual reality multidisciplinary team (VRMDT) meeting software may help enhance knowledge sharing between health care professionals and make meetings more efficient.

Objective: The objectives of this study were to introduce VRMDT software for enhancing knowledge sharing and to evaluate the feasibility and usability of the VRMDT for use by professionals in health care institutions.

Methods: We invited participants from The University of Manchester Faculty for Biology, Medicine, and Health who had a health care background. As this was the first stage of software development, individuals who did not usually attend MDT meetings were also invited via email to participate in this study. Participants evaluated VRMDT using a Meta Quest 3 headset, and software developed using the Unity platform. The software contained an onboarding tutorial that taught the participants how to select items, load and rotate 3D Digital Imaging and Communications in Medicine files, talk to a generative artificial intelligence–supported avatar, and make notes. After the evaluation (approximately 15 min), participants received an electronic survey using the Qualtrics survey tool (Qualtrics International Inc) to score the usability and feasibility of the software by responding to the 10-item system usability scale, and 12-point heuristic evaluation questions with Neilsen severity rating.

Results: A total of 12 participants, including 4 health informatics, 3 with a nursing background, 2 medical doctors, 1 radiologist, and 2 biostatisticians, participated in the study. The most common age bracket of participants was 20 - 30 years (6/12, 50%). Most of the respondents had no experience with virtual reality, either in educational or entertainment settings. The VRMDT received a mean usability score of 72.7 (range between 68 and 80.3), earning an overall “good” rating grade. The mean score of single items in the heuristic evaluation questionnaires was less than 1 out of 4 (the overall mean was 0.6), which indicates that only minor problems were encountered when using this software. Overall, the participant’s feedback was good with highlighted issues including a poor internet connection and the quality of the generative artificial intelligence response.

Conclusions: VRMDT software (developed by Sentira^{XR}) was developed with several functions aimed at helping health care professionals to discuss medical conditions efficiently. Participants found that the VRMDT is a powerful, and useful tool for enhancing knowledge sharing among professionals who are involved in MDT meetings due to its functionality and multiuser interactive environments. Additionally, there may be the possibility of using it to train junior professionals to interpret medical reports.

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KEYWORDS

knowledge sharing; multidisciplinary team meetings; artificial intelligence; heuristic evaluation; usability; virtual reality; VR; simulation; virtual environments; digital environments

Introduction

Overview

The United Kingdom's health care sector is facing significant pressures from increased patient demands and workforce supply issues. A need for efficiently connected health care employees is important for sharing knowledge and it is an integral part of knowledge management. During COVID-19, communication across sectors moved towards web-based communication methods [1-3], such as videoconferencing (eg, Microsoft Teams and Zoom), which helped to protect the lives of patients and staff [3-5]. To maintain knowledge-sharing practices among professionals, there are several professional digital communities [6,7]. The purpose of these professional digital communities is to get professionals with common expertise to share their knowledge without considering geographical barriers [6]. Virtual multidisciplinary team (MDT) meetings have been shown to have a visible role in maintaining communication among cancer care professionals to discuss, follow up, and set clear treatment plans [8]. Additionally, it has been shown to improve cancer patients' outcomes [9-13]. Traditional face-to-face methods of MDT have drawbacks that limit attendance including lack of time and funding [8]. Introducing new technology for communication has benefits, although there are also drawbacks such as reliance on bandwidth, increased conversation time, and loss of gesture communication that can be difficult compared with traditional methods, thereby directly affecting good decision-making [14,15].

The use of videoconferencing has surged as a communication method during and post-COVID, although it has limitations including the inability for natural F-2-F interaction due to the participants only seeing a video image. Additionally, smooth and stable internet network is required to ensure that video conferencing runs smoothly. Moreover, the inability to show 3D images compared with the virtual reality (VR) tools may be a distinct disadvantage [16]. As a result, the existence of a powerful web-based tool that simulates a real environment may have benefits. VR and augmented reality are increasingly being used in the medical field both for training and as a procedural aid [17]. VR is defined as "a three-dimensional computer-generated simulated environment, which attempts to replicate real world or imaginary environments and interactions, thereby supporting work, education, recreation, and health" [3,18]. In addition, the user can interact with avatars using generative artificial intelligence (AI) supported natural language processing (NLP) which further enhances the realism of the experience. It requires head-mounted displays, and either hand controllers or hand tracking in order to perform practical procedures [19]. The sense of presence is one of the key characteristics of VR that makes it different from other communication mediums [14]. The use of VR applications in the health care market has grown massively in recent years. In 2022, the VR health care market reached over US $2.3 billion worldwide, with 171 million VR users [20].

VR in health care has several benefits, such as facilitating training, education, and the development of technical skills. Additionally, VR is being used for a variety of purposes, including surgery and treatment, training, and patient therapy and rehabilitation [21]. Kyaw et al [22], illustrated that using VR applications improves professionals' skills, and knowledge compared with face-to-face communication and web-based digital education. In particular, it has the ability to negate the need for face-to-face contact, while maintaining the illusion of being with colleagues in the real world [23].

There are several factors that affect knowledge sharing in the medical imaging department at cancer centers, which are similar to those in most health care sectors [24]. MDTs are considered important departmental facilitators that enhance knowledge sharing among health care professionals [24]. MDT is considered a pillar of the best practices in cancer canters and plays an important role in cancer Treatment [25]. The United Kingdom's National Health Service definition of MDT is "a group of professionals from one or more clinical disciplines who together make decisions regarding the recommended treatment of individual patients" [26]. MDT in cancer centers is defined as the collaboration of several health care professionals in different fields engaged in the treatment of cancer with the overall objective of enhancing the rate of interpreting treatments of cancer patients, and patient care [13,26]. Cancer centers began to use a multidisciplinary approach in the mid-1980s, and by the 1990s, the MDT meeting was introduced as an instrument for providing coordinated, collaborative care, which allow a broader range of opinions on treatment plans [13,27]. In addition, it provides training for junior health care professionals. However, there are several barriers that contribute to not attending those meetings as per policy recommendations. These include time constraints, lack of departmental arrangements, geographical barriers among health care professionals, and shortage of staff [13].

In health care institutions, implementing new interventions such as VR among health care professionals may overcome current barriers and enhance knowledge-sharing practices to increase patients' outcomes and minimize medical mistakes. However, there are several challenges to implementing VR as a communication tool, including providing evidence that these technologies can save time, increase productivity, and reduce carbon footprint, without adding significant hardware costs and training time [28-30]. The aim of this research is to introduce new technology and perform a usability study of VR in MDT to investigate the feasibility and usability of using VR in cancer health care meetings.

Objectives

In this study, we developed a virtual reality multidisciplinary team (VRMDT) for enhancing communication with professionals, which was evaluated in terms of its usability by professionals from a variety of backgrounds.

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The aim of this study was to investigate the usability of newly developed VRMDT software that helps gather health professionals in a 3D immersive environment to aid communication and set a clear treatment plan for the cancer patient. The objectives of this study were:

- To introduce VRMDT software to health care professionals.
- Evaluate the usability, feasibility, and efficacy of VRMDT by applying the System Usability Scale (SUS), and identifying the problems with the user interface by using a heuristic evaluation questionnaire.
- Identify the strengths and weaknesses of using VRMDT.
- Determine if this technology has the potential to increase the number of MDT meetings in cancer centers locally and internationally.
- Increase awareness of using VR technology among health care professionals in cancer centers.

Methods

An Overview of VRMDT Software

The software was designed by our University of Manchester research team and developed using the Unity platform by Sentira^{XR} [31], which is a University of Manchester spinout that uses VR and generative AI NLP to create authentic training simulations for health care professionals and other disciplines. The designs of the VRMDT comprise:

- An onboarding section for those not familiar with VR.
- Options to select a health care uniform of varying color and add the name to be displayed above the head of each user's avatar.
- 3D VR meeting room with round table.
- Ability to display a 3D Digital Imaging and Communications in Medicine (DICOM) scan image in the middle of the virtual table to allow 3D visualization. Additionally, there is a screen in front of each user to few the DICOM images in a traditional 2D mode.
- A whiteboard for writing notes and drawing images.
- A laser pointer beside each user for pointing to specific locations on the 3D DICOM images.
- An interactive avatar that uses generative AI NLP to provide answers to questions from users in the room related to the patient's scans, condition, and patient history.
- A master control panel where patient DICOM images can be selected.

The VRMDT (Figure 1) is designed to allow health care professionals to treatment plan anywhere and at any time. To run the VRMDT simulation, a reasonable Wi-Fi connection (≥10 Mbps), head-mounted display, and controllers are required. Before entering the MDT room, the user had the option to undertake an onboarding scenario that introduced them to basic functionality such as picking up objects, talking to the avatar, selecting DICOM files, and making notes on a whiteboard. The user can then begin the simulation first by typing in their username (displayed over the head of their avatar) and selecting their outfit's color (Figure 2). In the VRMDT software, there is a round table fitting 10 users with a control screen that contains the setting options, selecting the patient DICOM files, and the option to move the control panel to another user. Another screen available to all 10 users displays the traditional 2D DICOM images for cancer patients (Figure 3B). Additionally, the meeting room contains a whiteboard to allow the user to make notes or draw diagrams (Figure 4B). In the middle of the meeting table, the 3D DICOM (Figure 4A) images appear with the facilities to rotate the images on the x-axis to help show any tumors or lesions. A laser pointer is available to each participant to help highlight a region on the 3D image (Figure 3A). DICOM images were retrieved from The Cancer Imaging Archive which are accessible for the public to download and use without ethical approval. The time zones for both the United Kingdom and Kuwait are displayed on the wall of the meeting room.

Generative AI NLP used the InWorld platform [32]. Voice cloning (voice of MA cloned) uses Eleven Labs software which is supported by InWorld [32,33]. Patient information and avatar background details were entered into InWorld and quality assurance was conducted to ensure that the responses from the generative AI NLP had an accuracy of 95% or greater. The generative AI NLP-supported avatar was placed in the meeting room (Figure 5) and allowed the user to ask questions regarding the medical condition of the patients. The Photon platform was used to allow users to speak with each other as they would with any teleconference software [34]. The purpose of the AI-supported avatar was to provide the MDT with specific details on each of the patients, such as name, age, status of the medical condition, medications, chemotherapy/radiotherapy received, response to treatments/medications, bloodwork, and patient concerns. Providing patient information via an avatar, removed the need for reading extensive text notes which is not ideal in a VR environment due to reduced visual resolution and an increased risk of cybersickness. It also allowed for one or more of the MDT to be absent and still provide the information.

For the implantation, the software required a direct connection with the Picture and Archiving and Communication System to visualize patient images. Additionally, the VRMDT contains instructions voiced over to guide the user throughout testing the software.

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Figure 1. The environment of the virtual reality multidisciplinary team software.

Figure 2. "On boarding" interface page for selection of the outfits, and the info that will appear on the user (such as name).

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Figure 3. (**A**) Two screens: a controlled screen and a screen to display the traditional 2D scan images. (**B**) Laser pointer.

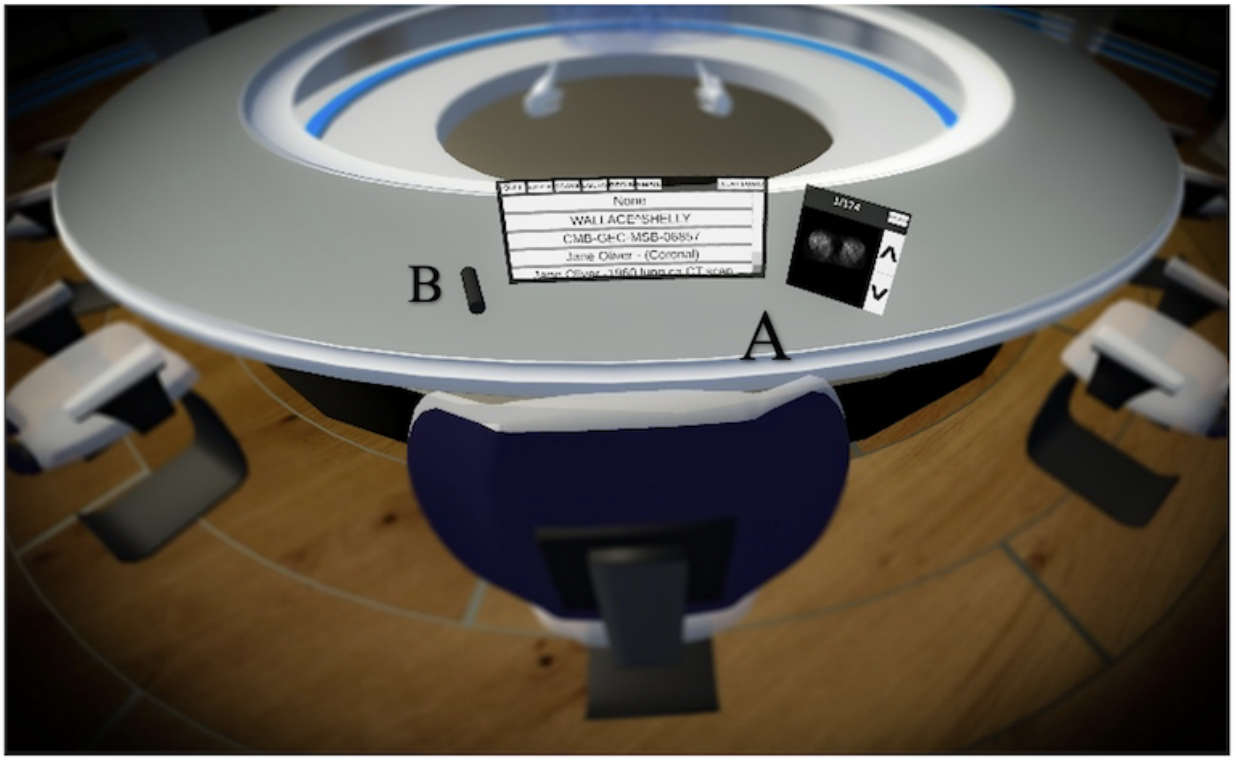

Figure 4. (**A**) The 3D Digital Imaging and Communications in Medicine (DICOM) images and (**B**) a whiteboard.

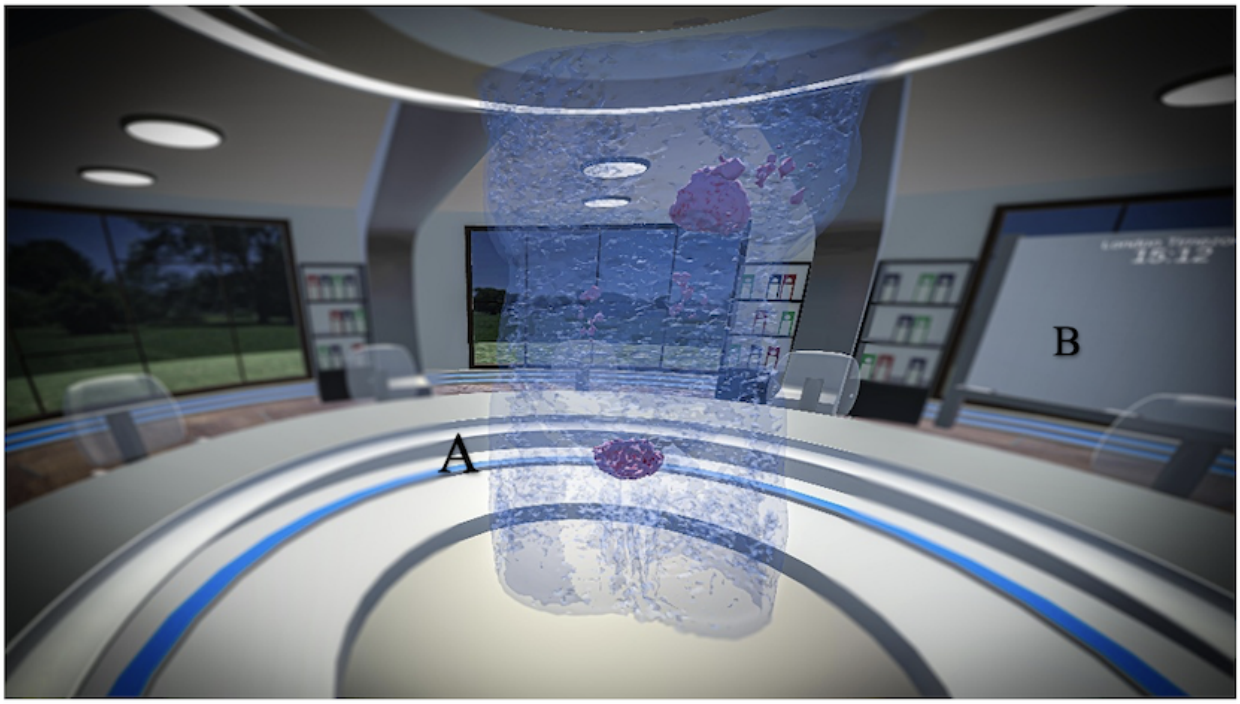

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Figure 5. Interactive avatar.

Participants

To be eligible for participation in this study, the participant had to have a health care background, with those recruited being postgraduate students and staff at The University of Manchester. As this was the first stage of software development, participants who were not routinely involved in MDTs were also invited to evaluate the software.

Participants were recruited via email with the inclusion criteria as provided in Textbox 1.

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Textbox 1. Inclusion and exclusion criteria.

Inclusion criteria

- Postgraduate students and staff at the University of Manchester.
- 21 years or older.
- Any gender.
- Health care professional background (including but not limited to doctors, nurses, and radiologists).
- Health care professionals who are involved in multidisciplinary teams.
- Willing to provide informed consent.
- English speakers.
- No pre-existing conditions that may cause discomfort or distress in a virtual reality (VR) environment.

Exclusion criteria

- People who do not read, speak or understand English, because the software is in English only.
- People who are unwilling to wear a VR headset.
- People who had a pre-existing condition that may cause discomfort or distress in a VR environment

Instruments

Validated usability and utility questionnaires were used to assess the simulation's efficacy, efficiency, and user pleasure [35]. Two methods were used to assess the usability evaluation: 10-item SUS, and 12-item heuristic evaluation questionnaires [36,37]. Upon completion of the trial, the SUS and heuristic questionnaire links were emailed to the participant to complete in their own time in Multimedia Appendix 1. The survey was built using the Qualtrics survey tool [38]. Participants were asked to assess the software based on 10-point scales [36] and answer statements using a 5-point Likert [36,39-46]. The SUS was selected as it is suitable method when applied to a small sample size (N less than 14) [39]. Questions 1, 3, 5, 7, and 9 are positive, whereas questions 2, 4, 6, 8, and 10 are negative. The 10 connected questions provide a full review of a product. The SUS yields a score between 0 and 100 [47]. A higher SUS score is associated with greater product usability.

To evaluate the user interface, and identify problems with the software, heuristic evaluation was used [37]. There are several heuristic evaluation questionnaires used to assess human-computer interaction [37,48,49]. In this study, we used the heuristic evaluation questionnaire based on Sutcliffe and Gault's heuristic evaluation of VR apps [37]. It consists of 12 heuristic items, including natural engagement, compatibility with the user's tasks and domain, natural expression of action, close coordination of actions and representation, realistic feedback, faithful viewpoints, navigation and orientation support, clear entry and exit points, consistent departures, support for learning, clear turn-taking, and sense of presence.

Our survey was an open survey (no password required) based on several previous VR usability studies but modified slightly to align with our simulation [36,37]. The survey was checked by 10 individuals with a health care background to ensure it was easy to understand. In addition to the SUS questions and heuristic evaluations, we also collected information on demographics.

Procedure

At the beginning of the evaluation, participants were given a brief introduction to the project and shown how to use the VR headset and controllers. For those new to VR, an onboarding section was available. The overall evaluation ran for approximately 10 to 15 minutes. If there was more than 1 participant present at the same time, we allowed them to trail the software together so that they could see and interact with each other through the VRMDT. For those who evaluated solo, one of the development team would join them in the simulation so they could experience multiuser functionality. The participants were emailed the survey to complete within a 2 week time frame with a reminder sent after this period. Evaluations were conducted between February and March 2024). All sessions are located at The University of Manchester in a dedicated VR lab.

Data Interpretation

The results are interpreted as a grade for the SUS and a mean for the heuristic evaluation. To provide the grade of the SUS, there are 4 ratings for SUS interoperation: excellent (score greater than 80), good (69 - 80.3), okay (score equal to 68), poor (51-68), and awful (less than 51) [36]. For the heuristic evaluation, each item was rated for severity using Nielsen scale (no problem=0, cosmetic problem=1, minor problem=2, major problem=3, and catastrophe=4), as shown in Table 1 [47]. Only completed questionnaires were included in the final results.

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Table . Nielson severity rating [48].

Rating	Definition
Don't Agree	I do not agree that this is a usability problem at all (there are no problems with usability)
Cosmetic problem	Needs not to be fixed unless extra time is available on the project (if there is time, aesthetic issue that only has to be fixed).
Minor problem	Fixing this should be given low priority (a low priority for a minor usability problem).
Major problem	Important fix required that should be given high priority (major usability problems, must be fixed right away)
Catastrophic	Imperative to fix this before product can be released.

Data Analysis

The final data were analyzed by entraining it into an Excel spreadsheet where the SUS score was calculated and the rate of the severity of each heuristic item based on the Nielsen severity scale for each item. The SUS questionnaire consisted of 10 questions. The score of SUS was calculated by adding the odd questions minus 5 and 25 minus the even number then multiplied by 2.5 [36]. On the other hand, the rate of heuristic severity was calculated by adding the number of statements and accepting the first statement which is no problem because it has zero value [37].

Ethical Considerations

The main purpose of this study is an anonymized evaluation of the VRMDT software in terms of its usability and utility. Therefore, the University of Manchester web-based ethics tool and the School of Health Sciences ethics representative confirmed that ethical approval was not required for this study. Consent was obtained from all participants that required them to sign a consent form. Anonymized responses were securely saved using the Qualtrics database.

Results

Participants

A total of 12 participants from a variety of health care fields were recruited (8/12, 67% female; 4/12, 33% male) with half of the participants being between 20 and 30 years of age (6/12, 50%). Most of the volunteers had a doctorate degree (8/12, 67%), with 4 having experience in health informatics. Most of the participants had no experience using VR before the evaluation. The demographic characteristics of the respondents are shown in Table 2.

Table . Demographics characteristics of the respondents (N=12).

Characteristics	Values, n (%)
Sex	
Female	8 (67)
Male	4 (33)
Age group (years)	
20-30	6 (50)
30-40	5 (42)
50-60	1 (8)
Highest education level	
Master degree	8 (67)
Doctorate degree	4 (33)
Background	
Nursing	3 (25)
Radiologist	1 (8)
Health Informatics	4 (33)
Medicine	2 (17)
Biostatistics	2 (17)

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Usability (SUS Questionnaires)

A total of 67% (n=8) of participants gave SUS scores greater than or equal to 68. Four (33%) of the participants scored "Poor" with the VRMDT, with the SUS score rate less than 62. The total mean score was 72.7, resulting in an overall "Good" rating. The SUS scores for the respondents are shown in Table 3.

Multimedia Appendix 2 presents the interpretation of the SUS. Based on the SUS items, the participants indicated that the software was easy to learn how to use, with a mean score of 4.1. The highest score was given to the item "I found the various functions in this software were well integrated (eg, whiteboard, and DICOM images)" with a mean score of 4.25. In contrast, the lowest score was given to the item "I thought there was too much inconsistency in this software" with a mean score of 1.5 where low scores are an indicator of better consistency.

Table . System Usability Scale (SUS) scores for respondents. Average=72.7 (Good).

Respondents	Results			
	X0[a]	Y0[b]	SUS	Grade[c]
1	19	15	85	A
2	17	17	85	A
3	17	12	72.5	B
4	12	19	77.5	B
5	16	9	62.5	D
6	7	14	52.5	D
7	16	19	87.5	A
8	14	14	70	B
9	14	9	57.5	D
10	11	10	52.5	D
11	18	16	85	A
12	18	16	85	A

[a]The total odd SUS questions–5.

[b]25–the total even SUS questions.

[c]Sum of X0 and Y0 × 2.5 (A=Excellent, B=Good, C=Okay, D=Poor, and F=Awful).

Heuristic Evaluation

The participants rated the severity of each heuristic item based on Nielsen severity scale. The results of these ratings are shown in Table 4. The value of the first severity scale "no problem" is zero, so it was not counted. We estimated the number and severity of reported problems for each item. For example, we received 3 statements that indicated the minor problems for the first item "natural engagement," 1 for the major problem, and 2 for the cosmetic problem. The total score was calculated by adding each heuristic item. All the items had a usability score of less than 12, with a mean score of less than 2. This indicated well-functioning software.

The summary rate is shown in Table 5. One of the respondents reported 32 problems and 3 indicated no problems at all based on 12 heuristic items.

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Table . Heuristics evaluation for each item with Nielson severity rating.

Number of items of the heuristics	Nielsen severity rating						
	No problem (0)	Cosmetic problem (1)	Minor problem (2)	Major problem (3)	Catastrophe (4)	Total	Mean
1. Natural engagement	9	0	2	1	0	3	0.7
2. Compatibility with the user's task	6	2	2	2	0	6	1.5
3. Natural expression of action	6	2	3	0	1	6	1.5
4. Close coordination	8	2	0	1	1	4	1
5. Realistic feedback	87	2	1	2	0	5	1.2
6. Faithful viewpoint	10	0	2	0	0	2	0.5
7. Navigation and orientation support	10	1	0	1	0	2	0.5
8. Clear entry and exit point	9	1	1	1	0	3	0.7
9. Consistent departures	8	3	1	0	0	4	1
10. Support for learning	7	0	4	1	0	5	1.2
11. Clear turn	11	0	0	1	0	1	0.2
12. Sense of presence	8	1	2	1	0	4	1

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Table . Heuristics evaluation with Nielson severity rating for each respondent (resp).

Number of items of the heuristics	Respondents scores												
	Resp.1	Resp.2	Resp.3	Resp.4	Resp.5	Resp.6	Resp.7	Resp.8	Resp.9	Resp.10	Resp.11	Resp.12	Total
1. Natural engagement	0	0	0	2	3	0	0	2	0	0	0	0	0.5
2. Compatibility with the user's task	0	2	0	0	2	3	0	3	0	1	1	0	1
3. Natural expression of action	0	1	0	0	4	2	0	2	0	2	1	0	0.7
4. Close coordination	1	0	0	0	4	0	1	3	0	0	0	0	0.4
5. Realistic feedback	0	0	0	2	3	0	1	3	0	0	1	0	0.8
6. Faithful viewpoint	2	0	0	0	0	0	0	2	0	0	0	0	0.3
7. Navigation and orientation support	0	0	0	1	0	0	0	3	0	0	0	0	0.3
8. Clear entry and exit point.	0	0	0	2	0	0	1	3	0	0	0	0	0.5
9. Consistent departures	0	1	0	1	0	0	0	2	0	1	0	0	0.4
10. Support for learning	2	0	0	2	0	0	0	3	0	2	2	0	1
11. Clear turn	0	0	0	0	0	0	0	3	0	0	0	0	0.2
12. Sense of presence	0	0	0	2	0	2	0	3	0	0	1	0	0.7
Total	5	4	0	12	8	7	3	32	0	6	6	0	0.6

Discussion

Principal Findings

The findings of this study provide valuable insight into the current usability and future improvements of VRMDT software. Previous research into VR meeting rooms indicates that they may be an efficient tool for improving communication during the planning of patient treatments [50]. Kirchgessner et al [51] illustrated that VR meeting rooms are more motivational than traditional technologies such as Zoom. Our work supported this

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with participant comments mentioning that presenting DICOM images in both 2D and 3D formats made the VR meeting more efficient than standard videoconferences with, respondent (D) mentioning "Being able to view images in 3D is the best thing about the VR software."

Our results found that the VRMDT software had adequate usability, with a mean SUS of 72.7, which is classed as "Good" as an overall interoperation. Most of the participants indicated that the simulation does not require intensive training to use it, suggesting that the inbuilt onboarding software is sufficient for training purposes, the respondent (C) said that "Browsing menus was simple and they were easy to use. Viewing DICOM images was intuitive." This is important for any health care institution as it will reduce the impact on existing training budgets and trainer time. Additionally, most of the respondents indicated that the software contains several useful functions, such as 2D and 3D DICOM views, a whiteboard, and an avatar that responds naturally to questions. These results suggest our software has clear advantages compared with conventional teleconferences. Another positive feedback was that the immersive 3D meeting room environment helped users feel as though they were in a real-world meeting. It is worth mentioning that a low score (mean=1.5) was given to the item "I thought there was too much inconsistency in this software," which indicated that the software was more relevant to its aim and objectives, and it performed well. The heuristic evaluation method indicated that the VRMDT has a good user interface with a low number of reported issues.

User Experience

Participant feedback highlighted a few areas for improvement. Respondent (A) illustrated that "The reason why I indicated there were some problems was due to the internet connection not being stable, which sometimes led to lagging and the AI avatar being slow to respond," and another respondent (B) said that "Software has potential but requires good Wi-Fi connection." Therefore, one of the major issues indicated by most of the users was the poor internet connection, which effected the sense of presence and interaction with some functionality. Additionally, the internet connection effected the interaction with the avatar which resulted in delayed responses to questions. This was an issue with the evaluation room which received a poor internet signal and was not an issue with the software. The other issue was related to the avatar. The respondents mentioned that the AI needed to be further developed to respond to more specific clinical questions other than age, general treatment, and health conditions. Additionally, it should be designed to respond to any questions with different accent words, the respondent (C) said that "It also struggled with my accent for certain words."

On the other hand, most of the respondents indicated that VRMDT was a powerful tool for sharing knowledge digitally compared with the other mediums because it contains several functions that make the environment immersive and very close to reality. Respondent (A) said that "it felt very futuristic, and I feel it will play an important role in future trans-geographical meetings." Therefore, this software would be a good alternative tool in the future when face-to-face communication is not possible. Additionally, it was suggested that VRMDT may be an alternative tool for training and assessing the knowledge of junior professionals instead of in-person training. In the future, I would like to update the software by adding several functions that help in upgrading the current software. For instance, the meeting room will be secure under each hospital's policies. In addition, those who have permission to enter this room can join this meeting after the invitation occurs. Moreover, It will contain the digital library, which contains the files and information about the cases that you want to make decisions regarding those cases.

Overall, the simulation was identified as a powerful tool for VR clinical meetings. In particular, it contained a functionality that allowed users to view both 3D and 2D DICOM images. While this has also been developed for off-the-shelf software (eg, [52]), the other software does not cater to a larger number of users generally seen at clinical meetings and lacks additional functionality such as a whiteboard, laser pointer, and AI-assisted avatar. Indeed, the avatar as an AI assistant was generally found to be very helpful in answering questions regarding the patients' condition and was found to elevate the usability of the VR meeting. Previous independent work has suggested that cybersickness is an issue for some users [29,30,53]. That issue was not indicated in the user's feedback from our study. The reasons for cybersickness not being an issue may include that the simulation was developed so the user can remain seated, which reduces excessive body movement both in real life and the simulation and provides a comfortable body position. Second, the headsets were modern (Meta Quest 3's with battery strap) and had a high frame rate (90 Hz), with a wide field of view (110°H × 96°V), which also helps reduce the risk of sickness. The Quest 3 headset is also reasonably priced (£480; US $596) and easy to set up and use, making it a cost-scalable solution. We also found that the software was usable in the Meta Quest 2 without significant loss in performance, with this headset being a much cheaper option (£200; US $249.45). Overall, the hardware experience was good, with users finding the headset very light on their head, and the controllers easy to use. As a first-time exposure to VR, the majority found the experience "amazing" enough that they recommended its implementation for future VR meetings.

Limitation and Future Studies

This study has several limitations that are worth documenting, and which we will consider for future developments. First, the VRMDT software was evaluated by a small number of health care professionals. Second, most of the volunteers were researchers, and many were from the health informatics field. Third, we encountered another issue that the evaluation took place in a room that had a poor internet connection. That limited the testing of the software efficiently, particularly the avatar generative AI NLP which had lag, and multiuser functionality where verbal communication between users was slightly delayed. Finally, the generative AI seemed limited in answering questions related to the patient's condition due to the lack of information available on the archival system.

Future research will need to consider testing using a more statistically powerful number of health care professionals

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involved in MDT meetings to determine how powerful the 2D or 3D DICOM images are at identifying cancer lesions. Second, to overcome the internet issue, we need to test the network stability before performing the usability study. Thirdly, the AI generative avatar needs to be supplied with more detailed knowledge about the patients so it can more accurately answer. Additionally, a longitudinal analysis after implementation would allow researchers to assess the impact of the software on productivity. Finally, a direct comparison of our software with current digital tools such as Zoom and Microsoft Teams will help to assess its usefulness in terms of features, and productivity.

Conclusions

In health care institutions, applying knowledge management is crucial to using resources in a good way to increase patients' outcomes, and reduce medical errors. Knowledge sharing is considered an important step for the successful implementation of knowledge management. There are several factors that affect knowledge sharing in medical imaging. These factors can be divided into 3 categories: individual, departmental, and technological factors. MDT meetings are considered a crucial departmental factor in enhancing knowledge sharing. However, time constraints and geographical barriers can impact knowledge exchange efficiency. We have shown that creating a VRMDT meeting room may be a powerful tool to reduce those barriers.

Our VRMDT allowed the volunteers to interact with other users, and use the specialized features that allowed them to understand the patient's condition and scans in a correct and efficient way with the volunteers rating the simulation as good. Our results suggest that multiuser VR meeting rooms that use generative AI, and the ability to visualize DICOM files in both 2D and 3D have advantages over currently used meeting methods and would benefit from further development and research.

Future development and research by our group would evaluate the usability with a wider range of health care staff and an increased number of volunteers, and overcome the limitations that were outlined in this study. We also intend to explore software security for connecting to health care systems in order to access patient scans and data and develop the software across platforms to include a wider range of VR headsets as well as PCs and tablets.

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Conflicts of Interest

None declared.

Multimedia Appendix 1
The consent form and the questionnaire of the survey.
[DOCX File, 28 KB - xr_v2i1e60651_app1.docx]

Multimedia Appendix 2
The interpretation of the System Usability Scale and heuristic evaluation.
[XLSX File, 14 KB - xr_v2i1e60651_app2.xlsx]

Checklist 1
STROBE Checklist.
[DOCX File, 35 KB - xr_v2i1e60651_app3.docx]

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Abbreviations

AI: artificial intelligence
DICOM: Digital Imaging and Communications in Medicine
MDT: multidisciplinary team
NLP: natural language processing
SUS: System Usability Scale
VR: virtual reality
VRMDT: virtual reality multidisciplinary team

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A Local Training Program to Increase Awareness of Emerging Extended Reality Technologies Among Health Care Professionals: Development Study

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Abstract

Background: Demands on health care services can greatly outweigh capacity. Multifactorial causative factors present great challenges, forcing the National Health Service (NHS) to increase efficiency and adaptivity. Concurrently, digital advancements are excelling and long-term plans for NHS sustainability are focusing on the use of technological interventions to benefit patients. As a result, integration of extended reality (XR) technology has become an important focus of health care research. However, models of how the digital literacy of health care workforces can be developed and how frontline staff can be actively involved in the design and development of creative digital interventions are lacking. Such programs are essential to allow the development and upscaling of digital innovation within the NHS for the benefit of the patients. Such a program has been developed in the Digital Futures research lab at Torbay and South Devon NHS Foundation Trust, representing one of the first immersive digital technologies research spaces embedded within the NHS. A “Digital Deep Dive” training program has been developed, allowing local health care workers to recognize the possibilities of digital health care technologies and supporting them in the evolution of ideas for potential bespoke digital solutions appropriate to their own patient groups and care pathways.

Objective: This paper aims to explain the development of this unique XR Deep Dive program and present the evaluation that informed future directions for its ongoing development.

Methods: The Deep Dive sessions were designed according to relevant pedagogic principles, including experiential, active, and contextual learning theories. Voluntary pilot sessions were held for local clinical teams comprised of junior doctors, consultants, nurses, and allied health professionals. Self-selection sampling was used. Participants completed an anonymous postsession feedback form, which was used to conduct a service evaluation. Data were analyzed using descriptive statistics (quantitative) and thematic analysis (qualitative).

Results: In total, 21 completed questionnaires were analyzed. Overall, the sessions were positively received: all participants reported increased awareness of the potential for digital health care innovation postsession and most found it useful and relevant to their clinical careers. Participants valued the sessions being grounded in a context relevant to local practice with opportunities to interact with the technology through the lens of use cases.

Conclusions: We have developed a unique training initiative providing contextually relevant XR technology awareness training for health care professionals locally. Despite the growing pace of digital health care innovation, we recognized a knowledge gap in our local workforce regarding the potential of XR technologies within health care. We responded by developing a training program grounded in the concept of digital co-creation—working with staff and service users to develop bespoke solutions integrated within patient pathways. The results from this paper will help to inform future directions for developing digital awareness training in our trust and have implications for wider NHS digital literacy training.

(JMIR XR Spatial Comput 2025;2:e57361) doi:10.2196/57361

KEYWORDS

health care XR; extended reality in health care; XR; virtual reality in health care; VR; digital awareness training; digital deep dive; digital literacy; emerging health care technology; digital future; extended reality; virtual reality

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Introduction

We live in an era where demands on NHS services can outweigh capacity. This mismatch in capacity versus demand is increasing and causative factors are multifactorial, including an aging population, significant years of underfunding, a reducing and inadequate workforce, and the COVID-19 pandemic. To meet these challenges, health care services must become more adaptive and efficient, while maintaining a world-leading standard of patient and clinician experience, service quality, and clinical safety. It is also an era where technological and digital advancements are progressing at an unprecedented rate.

The 2019 government-commissioned Topol Review [1] made important recommendations to ensure the NHS becomes a world leader in digital technologies utilization for the benefit of patients, and the necessity to grow the digital literacy of the health care workforce was further accelerated by the COVID-19 pandemic [2]. In a more recent development, the 2023 NHS Long Term Workforce Plan [3] underscores the significance of digital competencies and integration as crucial components in equipping the workforce to meet prospective service demands.

Extended reality (XR)—an umbrella term encapsulating the spectrum of immersive technologies from simple augmented reality (AR) through to complete virtual reality (VR)—has become a key focus of cutting-edge health care research [4], with its benefits becoming clearer through use in as many as 97 UK health organizations and 119 distinct health care research projects in 2021 [5]. The comparison of XR-driven practices to traditional methods in medicine [6,7], surgery [8,9], rehabilitation [10,11], and clinical education [12,13] have become important research foci in recent years. Ultimately, the effectiveness of XR technologies in enhancing clinical skills and patient outcomes has been well demonstrated [6]. However, as important as these research projects are, they are insufficient if not accompanied by programs of digital training and education to reach the wider workforce.

A review of the literature has indicated that, while studies exploring the use of XR in a health care setting are numerous, real-world working models of health care workforce XR awareness training are lacking, with no applicable papers yielded from our search. Thus, despite the advancements in XR technologies within health care, there is a notable gap in the literature regarding the training of health care professionals to effectively integrate these tools into clinical practice for the benefit of patients. We propose that in order for XR technologies to be truly embedded in the NHS, within clinical care pathways and for the benefit of patients, they need to be understood and utilized by clinicians and health care professionals within the correct health care context. Although many digital technology companies are innovating in this space, direct access to and collaboration with clinicians and patients from the first stage of their innovation is lacking, meaning there is often a mismatch or lack of true co-design in what is being developed and what is actually required.

In 2020, this paper's senior authors (JRL and NP) were profoundly aware of the lack of digital literacy within their local NHS health care workforce and the lack of successful fully integrated digital-clinical partnerships. Working together and alongside other experts to allow a true understanding of both the clinical and digital worlds, they set out to address this by conceptualizing and developing the unique "Digital Futures: Human Centred Digital Innovation" program [14], which was initially supported by funding from Health Education England. The idea was to allow a true understanding of both the clinical and digital worlds and develop innovations in the common ground between their areas of expertise. Thus, the conceptualization of a Digital Futures Research Lab built on an existing XR Lab, which had been in development at Torbay Hospital since 2016. The program represents one of the first immersive digital technologies research spaces embedded within the NHS to inform national insights into research and development of immersive digital technologies in health care.

The development of a "Digital Deep Dive" training program was one of the founding principles of the Digital Futures program. Its aim is to increase digital literacy and awareness in local clinical teams, supporting them to recognize the possibilities of digital health care technologies and evolve ideas for potential bespoke digital solutions appropriate to their own patient groups. The clinical user-led approach of joining digital experts and clinical experts was conceptualized to allow cross-fertilization of ideas and knowledge to support the creation of bespoke solutions within the patient pathways and represents a "bottom up" approach of educating staff groups in digital technology, which is now gaining national interest.

Through this paper, we aim to highlight how we have developed local XR Deep Dive Training Sessions as part of the Digital Futures Programme and evaluate the impact of pilot sessions we have delivered.

Methods

Design

The XR Deep Dive training sessions have been developed collaboratively between clinicians and digital experts at Torbay and South Devon Foundation Trust (TSDFT). The sessions were designed to be delivered to teams of health care professionals across the trust in the on-site TSDFT Digital Futures Research Lab. Since the authors consider cross-fertilization of digital and clinical expertise to be paramount in the development of digital interventions that are useful and usable in practice, the sessions were designed to be co-delivered by a clinician and a digital expert.

The Deep Dive learning strategy was originally conceptualized by a global learning design company in the early 2000s and has since been widely implemented across various industries to promote learning and process development within professional teams [15]. Core to the Deep Dive methodology is integration of key stakeholders, affording them the opportunity to experiment with new concepts and brainstorm how that concept could be adapted and successfully integrated into their own unique context [15]. This approach offers an ideal solution to the challenges of XR health care training we have previously described. Therefore, we have adapted the Deep Dive methodology to develop our local training program: we first

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introduce participants to the concept of XR, then we demonstrate its potential within health care, and finally we allow time, space, and support for teams to explore how the concept could be developed within the context of their own health care specialty for the direct benefit of local teams and patients.

To achieve this, we grounded our Digital Deep Dive session design in Experiential Learning theory [16]. A vital component of the deep dives is to showcase examples of embedded digital technologies in health care pathways across both our own trust and more widely, thus feeding the imaginations of the participants with the possibilities within the digital health care space by promoting hands-on experience and reflection [16]. In-session digital interaction was a key design priority, with time allocated to practical demonstrations and "digital playtime" allowing participants to trial the XR technology first hand. This also aligns with active learning theories and evidence that this type of digital interaction is a key component of achieving successful technology training [17]. The Digital Futures program has a "human first" approach to all its innovations, emphasizing how digital innovation can be utilized directly to improve patient care. In the Deep Dives, we therefore focus on technology in a humanistic sense—adopting this approach accentuates the personal, emotional, and psychological needs of the person in addition to their physical health needs, stressing the importance of treating each person as a unique individual, ensuring that care is patient-centred and that the health care experience is characterized by compassion, empathy, respect, and dignity [18]. We aimed to showcase how technology can be used to connect us with and value one another as fellow human beings, and so incorporated illustration of local use cases to provide context and authenticity. This design choice aligns with the goal of uniting concept with practice, which is central to contextual teaching and learning theory [19]. The informal learning environment was designed to encourage questions and discussion throughout, thereby supporting learners to develop a deeper understanding and explore different perspectives [20]. Time was also allotted at the end of the session for a mini focus group to further promote ideas for co-design and interdisciplinary collaboration of potential digital solutions. Sessions were designed to be delivered in a small group format (<10 participants), as this has been shown to foster better group collaboration, interaction, and discussion [20]. Finally, given the importance of posttraining follow-up to provide further support and ensure ongoing development [21], we considered how we would deliver postsession support as part of our program design—signposting to digital drop-in clinics to further improve targeted digital skills and share and refine ideas for future digital innovation was therefore promoted at the end of the Deep Dive sessions.

These design principles for the XR Deep Dive session are outlined in Figure 1, encapsulating the overarching aims of the training sessions, which are summarized in Figure 2.

Following the design phase, 8 voluntary pilot sessions were held between May 2022 and May 2023. Health care professionals—including resident doctors, consultants, nurses, occupational therapists, play specialists, and physiotherapists—from departments across TSDFT were invited between May 2022 and April 2023 via email and online trust advertising platforms to attend on a voluntary basis, therefore utilizing self-selection sampling [22]. Volunteers from all of these clinical groups attended sessions, with each session hosting between 3 and 8 participants to maintain the important small group sizes. Participants were invited to complete an anonymous postsession QR feedback form in Multimedia Appendix 1; by submitting this, participants consented for their anonymized comments to be included in this service evaluation. The Squire Guideline for Service Evaluation was used as a framework [23]. Free-text responses were evaluated by 2 authors (CG and PG) using thematic analysis, which is the accepted preferred method of interpreting qualitative data [24].

Each session was also observed by the senior author (JRL), who provided feedback on content and flow and suggested modifications. Using this feedback combined with the participant feedback, through an iterative process, the final content of the Digital Deep Dive sessions took shape.

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Figure 1. An outline of the design of the XR deep dive training sessions. VR: virtual reality; XR: extended reality.

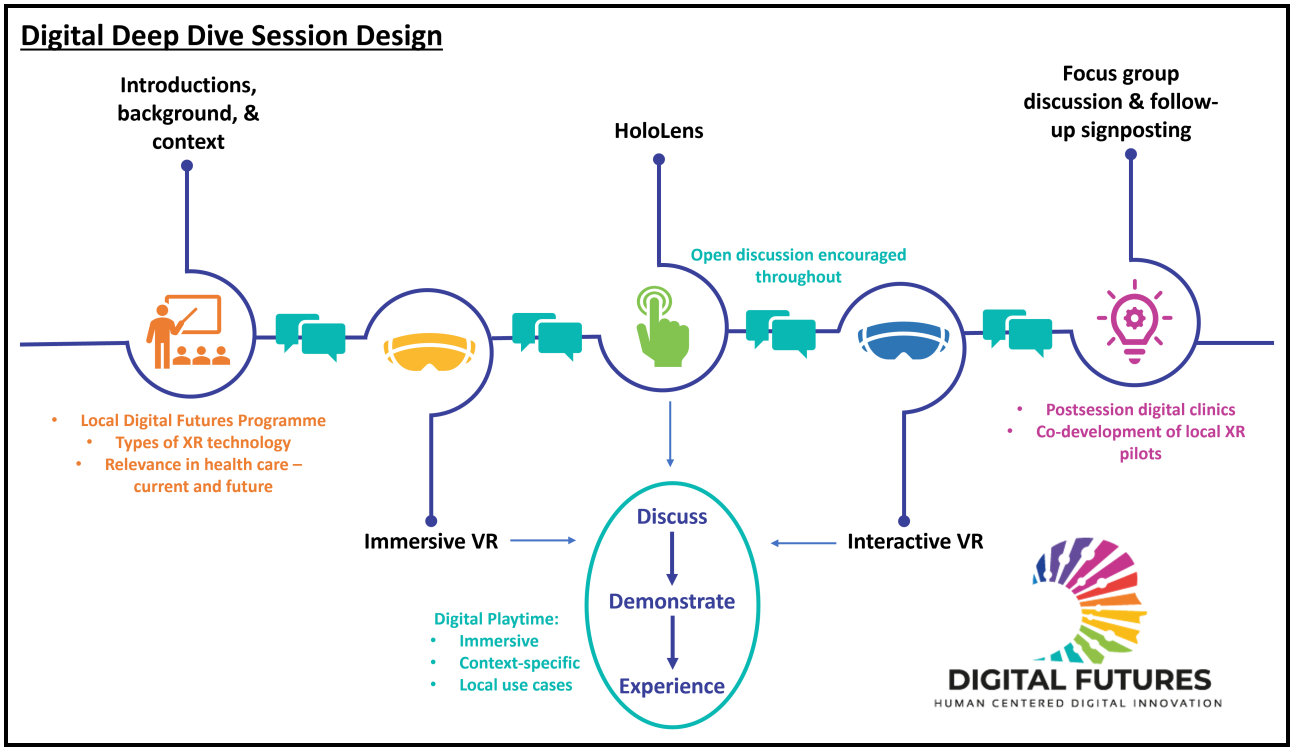

Figure 2. The aims of the XR deep dive training sessions. TSDFT: Torbay and South Devon Foundation Trust; XR: extended reality.

Digital Deep Dive Session Aims:

1. Provide brief *contextual education* about the *background* of XR technologies in health care.
2. Promote *awareness* of the XR technology equipment available for use at TSDFT as part of the Digital Futures Project.
3. To *showcase* how XR technologies have successfully been integrated into different health care environments both locally and further afield with a focus on "human first, patient-centered innovation" principles.
4. Provide opportunity for participants to use the XR equipment and explore its potential through *digital playtime*.
5. Encourage *imaginative exploration* and *collaboration of ideas* regarding how XR technologies might be further implemented into various health care settings.

Ethical Considerations

In line with guidance provided by the Health Research Authority and compatible local Research and Development policies at TSDFT, a formal ethics application was not required for this service evaluation project. Participants were made aware through a formal statement on the feedback form that their anonymous responses may be used for evaluation purposes and may be included in future published work.

Results

From a total of 8 sessions delivered to 35 participants, 21 completed questionnaires were received, with a mix of qualitative and quantitative responses (60% response rate). Quantitative responses were analyzed using descriptive statistics and free-text responses were thematically grouped and analyzed.

Quantitative Data

Data were collected through a series of closed questions and 5-point Likert scales. Quantitative data were collected in 2 categories: presession experience and postsession feedback.

Presession Experience

Results are displayed in Table 1. All participants who took part in the XR Deep Dive sessions had little to no experience of using XR technology previously. Although just over half of participants were aware of XR being used in a health care context—either generally or specifically—the remainder had never heard of XR technologies being implemented in health care, and none had any personal involvement in using XR

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technologies in a health care context. Further, most participants had never heard of the Digital Futures Programme at TSDFT and knew nothing or very little about current use of XR technologies in our local health care services.

Table . Quantitative data (presession ideas).

Question and answer	Number of responses (N=21)	Percentage of total responses
Before this session, what was your experience with virtual reality/augmented reality technologies?		
I had used these technologies a few times previously	11	52
I had heard of these technologies but had never used them	9	43
I had never heard of these technologies before	1	5
I had lots of experience of using these technologies	0	0
Before this session, how familiar were you with the use of digital technologies such as virtual reality/augmented reality in health care environments?		
I had never heard of these technologies being used in health care before	8	38
I had heard of these technologies being utilized in health care but did not have much knowledge regarding how	7	33
I had heard about specific projects involving these technologies in health care but have had no personal involvement	6	29
I have personally been involved in projects utilizing these technologies in health care settings	0	0
On a scale of 1 - 5, how much did you previously know about the digital projects ongoing at Torbay and South Devon Foundation Trust?		
1 (absolutely nothing)	16	76
2	2	10
3	3	14
4	0	0
5 (expert)	0	0
Had you previously heard of the Digital Futures Programme?		
Yes, and I knew what it was	1	4.76
Yes, but I didn't know what it was	1	4.76
No	19	90.48

Postsession Feedback

Results are displayed in Table 2. All participants indicated that they had a better understanding of the Digital Futures Programme and ongoing XR projects within the trust after taking part in the session. Most participants felt that the session was both useful and relevant to their future clinical careers and reported feeling inspired or very inspired to utilize XR technologies in their own health care specialty. Most participants indicated that they felt to some degree more confident in operating the XR equipment after the session.

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Table . Quantitative data (postsession feedback).

Question and answer	Number of responses (N=21)	Percentage of total responses
Do you now have a better understanding of the Digital Futures Programme and the current digital projects ongoing in Torbay?		
Yes	21	100
No	0	0
On a scale of 1 - 5, do you feel this session has inspired some ideas for how you might utilize digital technology in your chosen health care specialty?		
1 (not at all)	0	0
2	0	0
3	2	10
4	7	33
5 (completely)	12	57
On a scale of 1 - 5, how likely would you now be to get involved in a digital technologies in health care project in the future?		
1 (extremely unlikely)	0	0
2	0	0
3	4	19
4	7	33
5 (extremely likely)	10	48
On a scale of 1 - 5, how much more confident do you now feel in operating the virtual reality/HoloLens technologies compared to before the session?		
1 (not any more confident)	0	0
2	0	0
3	5	24
4	13	62
5 (entirely more confident)	3	14
Do you think this session was useful to your future career?		
Yes	20	95
No	0	0
Unsure	1	5
Do you think this session was relevant to your future career?		
Yes	20	95
No	0	0
Unsure	1	5

Free-Text Data

Free-text responses were collected in 4 main areas: presession ideas and motivation, session content and delivery; session relevance and utility; and postsession development. Following thematic analysis of the responses, key themes were identified in each of these areas. These themes are presented visually in Figure 3.

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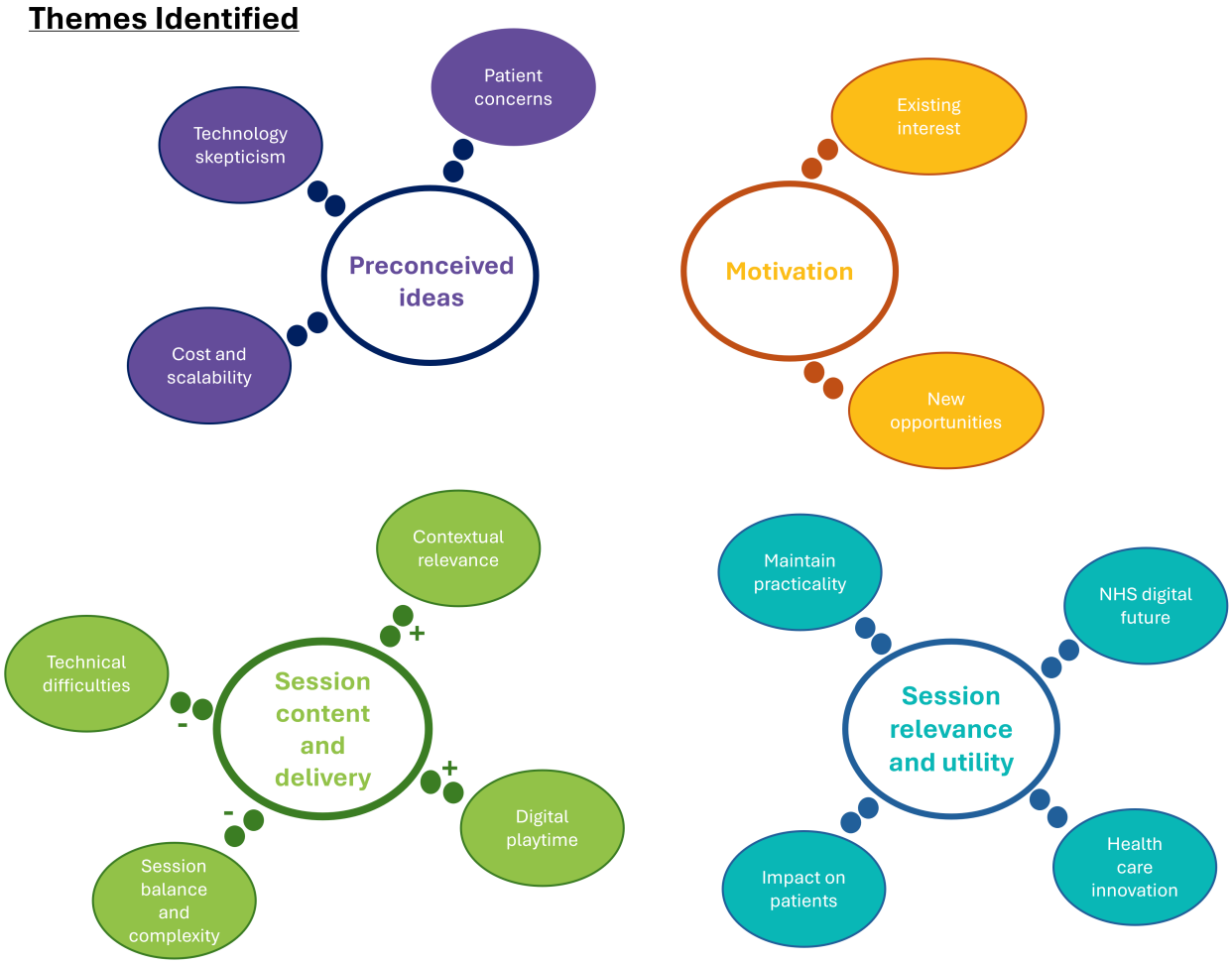
Figure 3. A visual representation of the themes identified from the free-text responses.



Presession Ideas and Motivation

Participants were asked 2 free-text questions in this area—the first related to presession ideas about technology use in health care and the second related to why the participant chose to get involved in a Deep Dive session.

Of the 21 respondents, 13 (62%) raised preconceived ideas about use of XR technology in health care. From these responses, 3 themes were identified: Patient Concerns, Technology Skepticism, and Cost and Scalability.

First, responses from 8 participants included concerns that highlight the preconceived ideas that technology would damage the patient-clinician relationship; technology use would lead to impersonal health care; and technology would present usability issues in certain patient groups, such as older patients. Together, these answers contribute to the dominant theme of Patient Concerns. Presented below are some direct quotes from the participants:

> *I wondered how user-friendly the equipment might be, especially for older patients.* [Participant 4]
>
> *Worried about virtual technology replacing physical examination with patients.* [Participant 19]
>
> *Negative impact on the clinician-patient relationship—not very personal.* [Participant 10]

Second, Technology Skepticism emerged as another preconceived idea. Participants expressed valid concerns about the relative infancy of XR technologies, particularly XR for health care, with some participant responses presented below:

> *I know of such technology in the gaming world, but...I was skeptical about its uses in healthcare.* [Participant 7]
>
> *Technology and its use in healthcare are still very much in their infancy.* [Participant 5]

The third theme that emerged from asking about preconceived ideas is that of Cost and Scalability. Four participants raised the concern that digital projects in health care may be unrealistic due to the costs involved, and its impact on availability and accessibility to the technologies. Some of the responses from the survey participants are presented below:

> *Very costly so thought it would not be very achievable on a large scale.* [Participant 8]
>
> *Funding is likely to be the big barrier.* [Participant 7]

Next, the motivation of respondents to participate in the Deep Dive sessions fell into 2 themes: Exploring an Existing Interest and Curiosity About New Opportunities. In response to the question about motivation for participating in the sessions, words such as “exciting,” “interesting,” and “unique” were used frequently.

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An existing interest in digital technology was identified by 7 participants as motivation for their involvement in the training sessions. One participant stated:

> *I am creative. I already know a bit about tech. I agree there is huge potential in using technology, specifically VR, to help people.* [Participant 2]

Further, 13 participants talked about being curious about what they perceived to be a new and interesting area. Multiple participants alluded to technology being part of the future in health care and that it holds many opportunities for development. Some quotes from the participants are presented below:

> *Interesting area of future development.* [Participant 20]
>
> *Wanted to hear more about what opportunity there was.* [Participant 12]

Session Content and Delivery

Participants were asked to identify the best thing about the session and whether they had any improvement suggestions. To ensure future session improvements, a specific question was also asked about any difficulties participants experienced when using the digital technology.

Positive comments about the session content and delivery were grouped in 2 themes: Digital Playtime and Contextual Relevance.

When asked to identify the best thing about the session, participants overwhelmingly gave answers that can be categorized into the theme of Digital Playtime. The hands-on digital experience integral to the session design was met with substantive positivity, with 19 of 21 participants (90%) citing the opportunity to use the technology in the session as one of the best aspects. Some example survey responses are below:

> *Fantastic to have hands on experience and understand more about how it all works.* [Participant 11]
>
> *Practical time with the headsets.* [Participant 13]

Next, participants particularly valued the use of local case studies to illustrate real-life application and contextual relevance, with 6 participants commenting that integration of use cases into the session was one of its best aspects. One participant said it was:

> *Brilliant to see the difference it's already making in the trust and the collaboration and partnership working already going on.* [Participant 11]

Participants were then asked about any specific technology difficulties experienced during the session and whether they had any improvement suggestions. Regarding technology difficulties, participants outlined 4 problems: connectivity issues (6 participants), motion sickness/nausea (2 participants), device fit issues (2 participants), and time to adjust (2 participants).

Eleven of 21 participants (52%) then made suggestions for session improvement. From the responses, 3 themes emerged: improvement of session balance, improvement of session complexity, and improvement of internet connectivity.

First, 8 participants gave answers that indicated better session balance would be welcomed. Integrating more digital playtime and less presentation time was frequently cited. Some participants suggested increasing the length of the session to allow for more digital playtime. One participant said:

> *At times there was too much tech talk which meant less time spent using the actual equipment, I think this could be streamlined to make the best use of time in the session.* [Participant 8]

Next, some responses suggested parts of the session were too complex and not pitched at the appropriate level. Participants highlighted that that there was "over-explanation of the technology" (Participant 1), "too much tech talk to start" (Participant 5), and that some parts of the session were "quite confusing" (Participant 4).

Finally, the quality of the internet connection was mentioned by 4 participants as an improvement suggestion, reinforcing that this was the main technology difficulty experienced during the sessions.

Session Relevance and Utility

Following the quantitative questions regarding session relevance and utility, participants were subsequently asked to explain their reasoning in a free-text question. Of the 21 participants, 20 (95%) thought the session was useful and relevant to their future clinical career—the single outlier was "unsure." When asked to expand on their answers, participants gave responses in 4 themes: Digital Future of the NHS, Potential for Health Care Innovation, Impact on Patients, and Ensuring Ideas are Practical.

When considering the relevance/utility of the session, 11 of 21 participants (52%) commented on the Digital Future of the NHS and the need for the workforce to be knowledgeable and prepared:

> *It will become more and more relevant over time.* [Participant 8]
>
> *Realise that tech is coming to the NHS and we need to be prepared to use it in our practice.* [Participant 10]
>
> *Tech is only going to become bigger in the next decade and clinicians need to catch up.* [Participant 3]

Next, 5 participants gave answers that fall under the theme of Potential for Health Care Innovation, recognizing areas for digital integration such as development of virtual patient assessment systems and the interpretation of radiological imaging. The technology still being "in its early stages" (Participant 9), however, was also recognized.

Three participants wrote directly about the impact of technology on patients, which was considered from different angles:

> *Still unsure whether this will benefit patients.* [Participant 9]
>
> *I can see how this type of thing can be used to benefits patients' care in the future.* [Participant 21]

Finally, 3 participants raised the point that that future innovations must be practical. Funding concerns were again

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mentioned as well as comments relating to the need to "work out what is realistic" (Participant 12) and the realization that some useful ideas "struggle in their execution" (Participant 2).

Postsession Development

To conclude, participants were asked for their suggestions on how the sessions should be followed up. From the 9 answers provided, 3 themes emerged: Clear Signposting, Focused Technology Support, and Exposure to Technology in Context.

The need for clearly signposted postsession support was raised by 3 participants, to allow ideas and interest generated in the session to be appropriately followed through. One participant talked about the benefit of having a "clear roadmap of steps from this workshop to generating ideas right through to fruition" (Participant 2).

Further, a need for focused technology support was identified by 4 participants, in order to provide more support to participants who had less experience with the technology itself or those who found adapting to the headsets more difficult. An example quote is included below:

> *Would need more time and support if taking this forward as a project.* [Participant 11]

Finally, 3 participants identified that they might benefit from the opportunity to have more exposure to the technology in context, perhaps with opportunities to trial it in clinical simulation or with real patients in the clinical environment.

Discussion

An XR Deep Dive training program has been created for local health care professionals, which has been evaluated as being clinically relevant, successfully increasing local awareness of current digital innovation projects within health care. It is also potentially useful to future clinical practice. This is the first step in developing and enhancing digital literacy and innovation within our health care staff across our integrated care organization.

Session Strengths

Participants indicated that their presession experience of using XR technology was minimal to nonexistent. The integration of digital playtime and first-hand exposure to the technology were reported as being an overwhelming strength of the session. Participants were encouraged to reflect on these practical experiences and engage in collaborative group discussion about potential applications and developments in their own health care settings. This experiential learning is a key component of adult learning theory, where learning takes place in a context-specific cycle of experience, reflection, conceptualization, and experimentation [16]. To provide this all-important context, relevant local use cases of successful XR interventions formed the basis of the practical demonstrations, fueling participants' imaginations of what is achievable within our own organization, thereby lifting the concept of XR integration from an abstract idea to a realistic possibility. For example, the following use cases (developed in-house) were explored (Figure 4):

1. Working with local clinical pain specialists, the Digital Futures team has been able to create a fully immersive tai chi on the beach VR experience (Figure 4A).
2. The successful integration of HoloLens technology to deliver immersive virtual clinics in the patient's homes.
3. How XR technology has been used at TSDFT to develop and deliver interactive empathy (Figure 4B) and patient management training (Figure 4C).

This contextual relevance was another key strength in our survey results, supporting the mantra that "seeing is believing" where emerging technologies are concerned [25].

Significant cultural challenges exist to the widespread adoption of XR technologies across all industries, including feelings of apathy, distrust, confusion, and skepticism [25]. Such cultural barriers are reinforced through our survey, with more than half of respondents exhibiting negative preconceived ideas about the use of XR technology in health care across 3 themes: Patient Concerns, Technology Skepticism, and Cost and Scalability. We believe that such concerns must be addressed head-on by providing staff with the opportunity to experience the technology in action, with time and support to understand its qualities and limitations as well as openly discussing and addressing concerns [25]. After taking part in a Deep Dive session, many participants acknowledged the potential of XR technology for health care innovation and had developed an appreciation of what might be realistically achievable at a local level.

Our co-creation approach to developing digital solutions that are useful and usable in practice was fundamental to the design of the Digital Futures Deep Dive sessions and to addressing these concerns. Having access to a digital expert during the session enabled practical discussions focused on achievable digital goals. Emphasizing cross-fertilization of clinical and digital expertise allows participants to understand that our local Digital Futures Programme aims to produce co-developed, intelligently implemented, and practically driven bespoke patient-focused health care solutions [26], and that digital care transformations are taking place in a positive sphere of negotiation and meaningful dialogue with key stakeholders, rather than being forced upon them [27].

The success of our XR Deep Dive training sessions is encapsulated and demonstrated by a significant number of participants showing active postsession engagement and interest in becoming involved in the local Digital Futures Programme, bringing with them the seedlings of ideas that were sown in the initial XR Deep Dive session.

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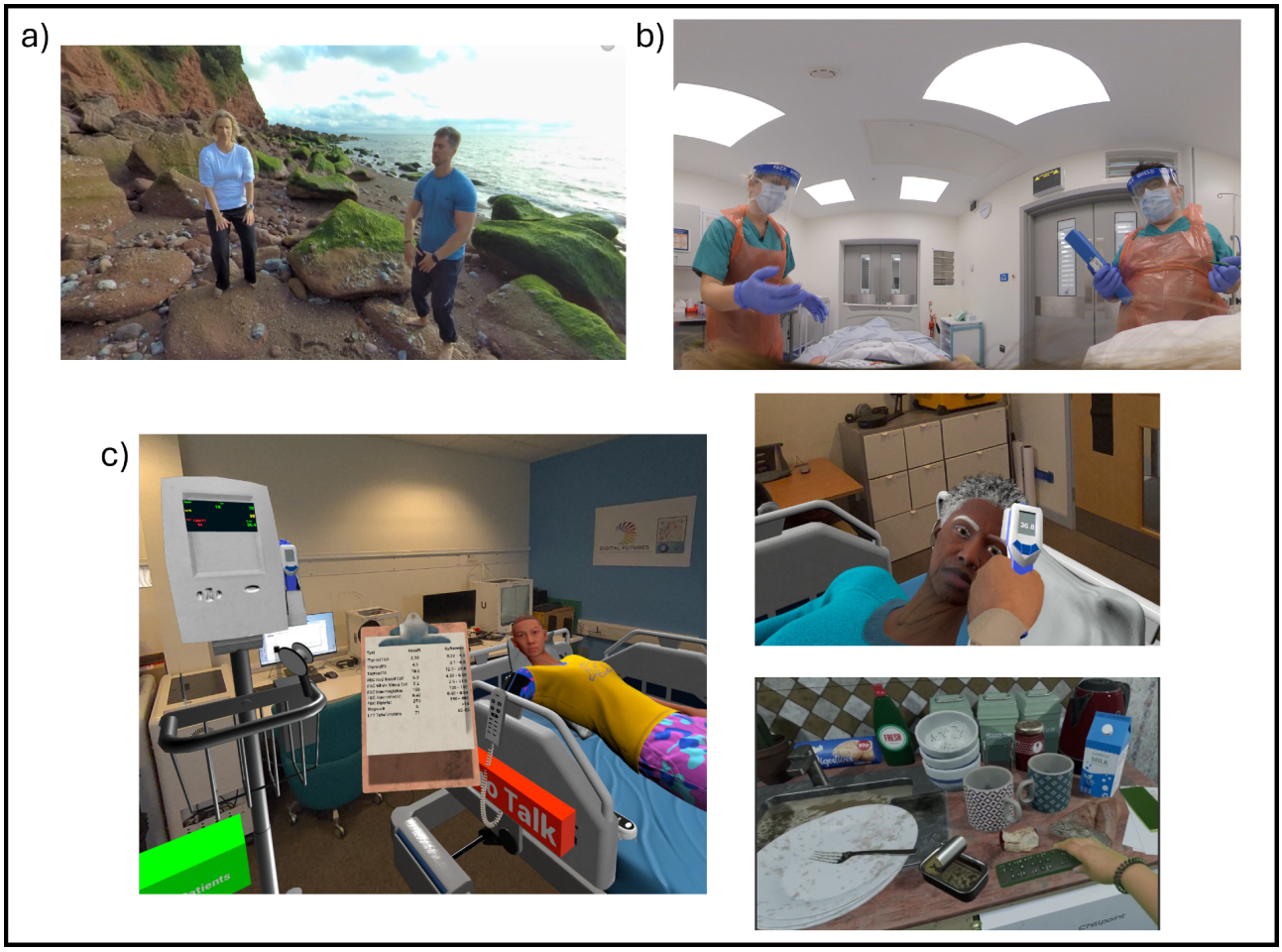
Figure 4. Examples of local XR use cases demonstrated during the XR deep dive training sessions: (A) immersive VR tai chi on the beach; (B) interactive VR empathy training; and (C) interactive HoloLens patient management training. VR: virtual reality; XR: extended reality.



Areas for Improvement

Our survey revealed that participants felt the balance and complexity of the session could be improved, with respondents requesting more hands-on time with the XR headsets and less presentation time, reinforcing that the strength of the session lies in its integration of practical digital experience. As a result of this feedback, we were able to perform a review of the session design after the first few deliveries and made some intermediate interventions, including increasing the session length from 90 to 120 minutes with more dedicated practical time, streamlining the session presentation, and simplifying the digital-focused background information. This resulted in improved feedback, with improvement comments under the themes of "Improvement of Session Balance" and "Improvement of Session Complexity" occurring far less frequently in the later pilot sessions.

Approximately one-quarter of respondents talked about connectivity issues when asked whether they experienced technology difficulties during the session. Resolution of connectivity issues subsequently became a theme for improvement. Such connectivity issues are unfortunately widespread in the NHS—a survey found that 58% of NHS staff had experienced Wi-Fi blind spots in their trust buildings, and two-thirds agreed that digital innovations in their team had been abandoned due to poor connectivity [26]. This is a limitation of NHS infrastructure and is not within the abilities of this paper's authors to change. However, we recognize—like 98% of NHS staff—that Wi-Fi infrastructure and mobile connectivity are crucial to the future delivery of innovative health care [26] and will therefore continue to play our part in campaigning for improved connectivity as part of our local Digital Futures initiative.

Principal Findings

The Digital Futures Lab is on-site in our NHS trust, and it is bespoke and evolving. It was built to develop and support the digital literacy of all health care staff in our trust. Our evaluation found that most participants came to our training session with no or little knowledge about the use of XR technologies in a health care context or local XR development projects. As expected, most participants had never heard of our new local Digital Futures Programme and were not aware of the investment and facilities available within our own organization recently. Without awareness of the opportunities available, clinical teams simply cannot drive digital innovation. This aligns with the findings of a 2023 survey that lack of digital knowledge and skills within health care teams was considered by three-quarters of surveyed NHS workers to be a significant barrier to innovation [26]. Furthermore, this emphasizes the Topol recognition that a culture of NHS digital innovation can only be achieved when coupled with a learning culture that supports frontline staff to explore new technologies and the opportunities they present for patient care [1].

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An integral component to building such a culture is having a cohort of learners who are motivated to explore the opportunities presented by advancing digital technologies. An appetite to explore and embrace digital advancements to transform patient care has been identified among health care workers on a national scale [26]. Similarly, many participants in our survey acknowledged the upcoming digital age of the NHS, recognized digital technology as a tool for innovation, and cited their curiosity to learn about such innovation opportunities as motivation for seeking digital training.

Overall, in our local health care workforce, there exists a knowledge gap regarding XR potential and current local opportunities coupled with a strong desire to rectify this, indicating a clear need for the XR Deep Dive training session we have created. After taking part in our session, all respondents reported an increased awareness of local digital innovation and most felt inspired to get involved in future digital projects themselves, highlighting that our sessions have been successful in meeting their aims.

Future Directions

Feedback from pilot sessions has supported the need for our new XR Deep Dive training sessions and has informed the refinement of the original session design as part of a quality improvement cycle. Intermediate interventions to address initial concerns regarding session balance and overcomplexity have already been successfully implemented, and there remains scope for further improvement. For example, future directions of the XR Deep Dive training program may involve a tiered approach to cater for participants of different starting abilities and experiences, potentially incorporating "beginner," "intermediate," and "advanced" training sessions, which can be accessed either in isolation or as a progressive series. Future evaluation of such an expansion of the training program would offer further insights into how we can successfully fulfill the NHS Long Term Workforce Plan of upskilling and training staff in our NHS trust to maximize digital technologies to improve health care delivery for the benefit of patients locally [3]. Future research will also inform us about the different technology behaviors of individuals and help us develop insights on how behavior change can be encouraged.

Digital transformation, and XR health care technologies in particular, are rapidly evolving and driving change. Maturation of hardware and software means content is becoming more sophisticated, user friendly, and seamlessly integrated into the real world [25]. Training programs—such as the one we have developed—will therefore also be required to evolve. Regular periodic reviews of the session content must be scheduled with updates as required, to ensure the training does not become outdated and irrelevant. Further, as use of technology in our local trust increases, the use cases demonstrated in the XR Deep Dive training sessions must also be reviewed to ensure they remain current and engaging. Showcasing use cases tailored to the participants' own context will become easier as more local health care specialties adopt XR innovation.

As the training program grows, we must ensure its sustainability. This will involve the recruitment of local "clinical digital champions"—as identified in Topol [1]—to deliver peer-to-peer training, sharing their knowledge and unique experiences. Recruitment and training of digital experts must also be maintained—and increased proportionately—at the trust level. Ongoing funding must be secured in line with the program growth, which will require a funding strategy as part of the wider Digital Futures Programme in our trust. A robust and sustainable follow-up support model must be established to bridge the gap between this initial training session and adopting XR solutions in the clinical environment. Sparking the imagination of what is possible in the realm of local XR health care technology is trivial if participants do not subsequently have access to the technical support and expertise required to conduct trials within their own clinical spaces. We have already begun to tentatively explore a model of "Digital Clinics" for this purpose, but data from our survey emphasize how follow-up support must be focused, context-specific, and clearly signposted. Refining a sustainable follow-up model that meets these criteria is the next step in the development of this training program.

Finally, digital health care transformation is certainly not without its ethical challenges, including concerns around access, consent, inclusivity, privacy, and dignity [1,28]. As digital innovation training evolves, it must incorporate these ethical discussions and continue to tackle cultural barriers. Encouraging honest and open dialogue will be key to finding workable local solutions to ethical challenges and ensuring a true co-design culture is adopted. Our survey highlights staff concerns that XR technology will remove the personal aspect from patient-clinician relationships, thereby dehumanizing care. This concern is also recognized in the Topol review. Our local Digital Futures goal aligns with that of Topol: to focus on how digital technologies can enhance, rather than retract from, our human interactions. We are proud that our local digital projects prioritize the humanistic aspects of care and have built our training to showcase this. As digital innovation and the associated awareness training evolves, we must not lose sight of our core values.

Limitations of This Paper

This paper explores a small, single-center pilot of a new local training intervention. Its findings are intended to inform future directions in our own trust and may not be generalizable to a wider context.

First, given the voluntary, self-selection sampling used to recruit participants to the Deep Dive pilot sessions, it is likely that our survey suffers from selection bias, capturing the views of staff who were already motivated to undertake the training in the first place. Given that a significant number of survey respondents talked about a prior interest in technology and a curiosity to explore new digital opportunities further as a reason to sign up to the pilot sessions, it is likely that our data do not capture the cohort of staff in our trust who are true digital skeptics. To obtain a wider spectrum of opinions, for future iterations of this pilot, we should aim to recruit staff members who do not have prior motivation for engaging in digital training sessions. This will provide insights into how we can effectively engage digital-skeptic staff to engage in the technology

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advancements being implemented both in our local trust and nationally within the health service.

Second, feedback was collected via an online feedback form accessed via a QR code at the end of the session. Not all session participants completed the feedback (60% response rate), possibly owing to the fact there was no physical form and they never got around to submitting it online. Concerns around nonresponse bias must therefore be considered when interpreting our findings. Obtaining feedback online is an established challenge [29]. To ensure a more complete representation of participant views in future, it may be preferable to supplement a feedback form with a recorded feedback focus group at the end of future sessions.

Conclusion

Having identified a gap in real-world working models of health care workforce XR awareness and development training, we have designed and implemented XR Deep Dive training sessions for health care staff. This was one of the principle aims of our Digital Futures Programme. These sessions provide contextually relevant XR technology awareness training and are the first step in working toward the goal of nurturing digitally literate health care workforces who have the knowledge and skills to embrace transformative technology in the improvement of patient care, as per Topol [1]. Our session design draws on Experiential, Active, and Contextual Learning theories by showcasing local use cases of the technology in practice, prioritizing hands-on digital playtime and emphasizing the vital cross-fertilization of clinical and digital expertise in the co-creation of digital solutions that are useful and usable in practice. Data from the pilot sessions suggest that we have created a training session that is engaging as well as relevant and useful to future clinical practice. The results from this paper will help to inform future directions for developing digital awareness training in our trust.

Acknowledgments

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Data Availability

The datasets generated during or analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

CG wrote the manuscript and carried out thematic analysis of results. PG carried out thematic analysis of the results. JRL, NP, CG, and JW were involved in the design and delivery of the Deep Dives training program. JRL and NP secured funding and originally developed the "Digital Futures: Human Centred Digital Innovation" program and set up the Digital Futures Lab at TSDFT. All authors reviewed and edited the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
The questionnaire survey used to collect participant feedback following pilot XR Deep Dive training sessions.
[PDF File, 483 KB - xr_v2i1e57361_app1.pdf]

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Abbreviations

AR: augmented reality
NHS: National Health Service
TSDFT: Torbay and South Devon Foundation Trust
VR: virtual reality
XR: extended reality

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Virtual Reality Application for Teaching Complex Congenital Heart Defect Anatomy: Design and Development Study

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Abstract

Background: Medical education still faces challenges in teaching complex human cardiac anatomy to a wide range of learners, especially in the subject of congenital heart defects. Traditional educational methods such as cadaver dissection and the use of textbooks still face some limitations, for example, specimen availability and student comfort. The objective of this research is to use newer technologies, like virtual reality (VR), to teach the anatomy of congenital heart defects (CHDs) of 3D heart models from real computed tomography (CT)-scan images, to offer a more profound learning experience for learners and mentors.

Objective: The objective of this study is to propose and implement an innovative pipeline for a VR-based educational application for CHDs, and to assess its acceptance and suitability for medical education by evaluating potential future users.

Methods: Heart images of anonymized CT scans were used to create high-fidelity 3D cardiac models, using Materialise Mimics Core and 3-matic Medical. These models were next integrated into a Unity-powered VR application. A heterogeneous group of cardiologists, biomedical engineers, and medical trainees visiting the Visible Heart Laboratories was invited to this pilot study to assess perceived effectiveness and satisfaction of this VR app for CHD education.

Results: A total of 9 participants were included in the study, comprising 4 (44%) cardiologists, 2 (22%) biomedical engineers, and 2 (22%) medical trainees. Mean perception based on potential for CHD education of this VR-app (4.56, SD 0.53), was higher than traditional methods (3.22, SD 0.026; P=.008). Participants rated this application more suitable for medical students (mean=3.22, SD 0.83; P=.02) and patient education (mean=4.11, SD 1.05; P=.03).

Conclusions: Our developed VR application offers an innovative approach to teaching the complex cardiac anatomy of CHDs using models from CT scans. This research shows how newer technologies can be optimized for medical education with the advantage of 3D visualization and a teaching environment without geographical limitations. Future work should focus on Extended Reality (XR) integration, adding more heart and organ models, as well as performing long-term efficacy studies.

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KEYWORDS

medical education; virtual reality; congenital heart disease; congenital heart defect; anatomy; innovation

Introduction

Current curricula in medical education often face the challenges of keeping pace with newly developed teaching methods: for example, these include those introduced by technological advancements such as the use of web applications, virtual reality (VR), and extended reality (XR) [1]. The study of complexities and variations within human anatomy has historically been based on the use of fresh cadavers, hearts preserved in formaldehyde, and the study of anatomy textbooks [2,3]. The use of new technologies in medical education, such as XR and VR, is particularly valuable given the complex spatial architecture of the human heart [4,5]. This complexity is further amplified in the context of teaching congenital heart defects (CHD), where anatomical variations are highly diverse. Students face significant cognitive challenges in understanding these conditions due to the intertwined vascular structures, dynamic relationships between cardiac components, and the wide variability of defects that can occur from one patient to another [5,6].

The use of traditional dissection and the study of macroscopic anatomy, as well as generating human models, while of

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particular importance in acquiring practical skills that are difficult to replace [7-9], are methods with numerous limitations. Today, many medical school anatomy laboratories have difficulties maintaining adequate quantities of specimens in the needed conditions for educational study [10]. The practice of only studying surface anatomy falls short when one needs to understand complex anatomical details, such as vasculature, complexities of nervous innervations, associated congenital heart defects, and other intricate aspects [7,10]. It should also be noted that some students don't have access to a dissection opportunity, and in others, such environments can be a source of stress and anxiety [11,12]. In this regard, the integration of XR technologies into medical education represents a significant advancement for many learners in the application of a better understanding of complex human anatomical and clinical knowledge required in healthcare or the medical device field.

Extended reality technologies are an umbrella term that encompasses VR, augmented reality (AR), and mixed reality (MR) educational tools [13,14]. In general, VR is typically described as a computer-generated three-dimensional space that simulates the presence of physical objects through multisensory interactions, creating immersive experiences in which users perceive artificial worlds as if they were real. It can also be characterized by its capacity to be a computer-generated space where multiple users can have simultaneous access and thus participate in shared activities [15-17]. While different types of metaverse share common features such as head-mounted displays for virtual immersions, motion tracking with 6-degree of freedom for real-time interactions, haptic feedbacks, and spatial audio to create a more immersive experience [15,18], VR differs from XR in that XR superimposes digital information onto the user's real physical environment, while VR completely isolates the user from the outside world, immersing them in a fully simulated virtual environment with which they can interact [15,19].

According to recently reported studies on knowledge construction, perhaps a more effective way to better retain knowledge is through "active learning" or "learning by doing." This implies that individuals better acquire critical knowledge through interactive and self-directed activities, such as those offered by VR [20]. The advantages of VR in educational settings include its ability to overcome physical barriers, allowing learners to engage with complex content regardless of location or access to physical resources [15]. This feature also enables collaboration among multiple users, providing greater flexibility to develop new applications and initiate diverse activities [6]. For example, by engaging with these VR applications, students can pursue self-directed learning and address their questions with greater autonomy [15]. Within the Visible Heart Laboratory, virtual platforms with interactive 3D models have been successfully used by medical students and residents for training relative to both cardiac physiology and transesophageal echocardiography [4,21]. By leveraging an extensive collection of over 650 perfusion-fixed human cardiac specimens, our laboratory continues to generate high-resolution 3D computational models that, in turn, facilitate precise virtual placements of medical devices [6]. Additionally, multiple applications have been developed and used in the field of presurgical planning, using VR in our facilities, and the unique availability of an extensive range of fixed human hearts. This approach has been the cornerstone for generating multiple educational and collaborative tools such as our Stenting simulator, Seldinger technique guidewire simulator, and augmented reality applications like the "Heart to Learn App" [22,23].

To evaluate the relative efficacies of using VR for human anatomic education, multiple research groups have consistently described the associated improvements this approach offers. For instance, Minouei et al [24] and Liu et al [25], in systematic reviews, found that VR commonly enhanced the students' academic progress in terms of theoretical knowledge, practical proficiency, and overall satisfaction when used as a supplementary methods to other teaching approaches. Similarly, Baek et al [2] described 6 VR applications for the visualization and study of anatomical structures. They recommend that the use of these applications should be tailored to the student's needs and suggested several ideal conditions for the creation of a VR application, such as the need for detailed tutorials, a realistic description of the anatomical model, motion animations, periodic updates, cost effectiveness, and high resolution. Other educators have conducted a controlled clinical study, examining the roles of interactive 3D models in medical anatomy education; in such, 200 medical students were surveyed, and the results showed a statistically significant improvement in post-test knowledge when compared to the control group [26]. Further, Garcia-Robles et al [27] and Salimi et al [28], in their meta-analyses, demonstrated that XR generated increases in knowledge compared to traditional learning methods, especially when used with complementary resources. They noted that these learning approaches were most beneficial for undergraduate students, of whom 80% reported that when they used such VR tools, they were useful for learning complex anatomies. Similarly, Liu and Wang et al [25] reported a higher satisfaction rating in groups of health care workers and students who used VR compared to other learning methods.

It is also important to consider the limitations of VR use in some individuals, which can generate adverse effects such as visually induced motion sickness (VIMS). In a pilot study, VIMS was reported in 32% of participants, of which 40% stated that experiencing VIMS could negatively impact their learning process when using VR educational tools [29].

One should also consider that gaps currently persist in the specific implementations of video game engines for applications in educational cardiac modeling, such as the implementation of haptic devices to simulate organ deformation by touching it, gamification strategies (rankings, scores), developing effective ways to reduce side effects (blurriness, dizziness), and performing more studies with a large sample size to assess the best way to deliver immersive education to students; this is particularly true in the field of CHD [30,31].

This study proposes an innovative pipeline that combines high-fidelity 3D modeling based on real tomographic data with dynamic visualization of myocardial layers and blood volume, and the implementations of such in Unity 3D [32], to create a VR-based application that can be used for educational purposes

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in CHDs, we want to measure acceptance and suitability of this application on medical practice by assessing possible future users of the application.

Methods

Image Acquisition and 3D Modeling

The methodologies employed in our work were developed in several sequential stages, beginning with the acquisition and processing of medical images. After informed consent, collection of primary and secondary medical data and information de-identification, anonymous DICOM images from patients were obtained through computed tomography (CT) from cases shared by Hospital La Cardio (Bogotá, Colombia), and from the anonymous database within the Visible Heart® Laboratories (University of Minnesota, Minneapolis, USA). Following their initial clinical use, associated images were anonymized using the safe-harbor method to ensure patient confidentiality; the resulting dataset contained only the anonymized DICOM files required for 3D reconstruction. No additional consent was required during the development of this study, as the anonymized data posed no risks to patient privacy.

These image datasets were processed using Materialize Mimics Core 27.0 software to perform semi-automatic segmentation of cardiac structures. As these investigations and development of de-identified 3D computation models did not directly involve human participants or use identifiable personal data, that is, they did not require approval from an ethics committee.

In general, the segmentation process included automatic image alignments to ensure anatomical symmetry, followed by blood volume segmentations of ventricles, atria, and great vessels using adaptive thresholding (HU: approximately 200 to 1500) via the software's CT Heart tools. For a given heart, specific cardiac defects were identified, such as interventricular communications, interatrial communications, patent ductus arteriosus, and/or others. Anatomical borders were manually refined using the Edit Masks function, achieving precision up to 1 mm, and internal hollowing was applied to simulate cardiac cavities.

Subsequently, these segmented congenital heart models were exported to Materialise 3-matic Medical 19.0 for optimization and final 3D modeling. At this stage, topological mesh repair was performed, eliminating nonmanifold triangles, and cardiac valves were added using a parametric model library, adjusting their scale to the specific dimensions of each patient's heart. Anatomical textures were applied, and surfaces were smoothed using the Smooth Surface software module. The final models were exported in OBJ format, with mesh parameters optimized for VR performance.

VR Application Development

During the development of the VR-based educational application, Unity software 2021.3 LTS with XR Interaction Toolkit 2.3 was used. The generated 3D heart models were then obtained from 3-matic and were imported to Unity as optimized mesh assets. To ensure complete visualization of the cardiac structures, backface culling was disabled, allowing the users to actively "cut" into the heart and analyze the internal structures of the given 3D heart model.

To optimize anatomical accuracy, custom shader-based materials were added with deoxygenated and oxygenated blood volumes color-coded with blue and red, respectively, as well as myocardium rendered in flesh tones, and the various pathological defects were highlighted: remaining visually coherent under a dynamic real-time clipping system, developed using shader programming.

A floating in-world Canvas menu was designed using Unity's XR Ray Interactor system, allowing users to have seamless navigation between heart models, toggling different cardiopathies, and scrolling texts. Beyond single-user exploration, this unique educational application was designed to support real-time multiplayer interactions, using Unity's Netcode for GameObjects: users can communicate in real time using integrated Vivox Voice Chat and Photon PUN networking.

While the initial release targets personal computer–based VR setups, a standalone version was optimized for lower-performance hardware using texture compression and GPU instancing to maintain rendering efficiency. Compatibility with OpenXR ensures broader accessibility across multiple headsets, including the Valve Index, HTC Vive, and Oculus Rift.

VR App: Innovative Functionalities

Our developed educational application includes a floating menu that categorizes heart defects into cyanotic and noncyanotic (Figure 1), with dynamic descriptive text incorporated within relative to each heart condition to be studied and explanatory images of predictive blood flows. Users can move the menu in the VR space as needed. The main functionalities allow users to manipulate cardiac models, including scaling, free rotations, and the ability to perform multiplanar cuts using Shader Graph. Additionally, there is an incorporated pointer feature that any of the users can use to mark the given defect to be mentioned or mark a specific location on the heart (Figure 2).

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Figure 1. Congenital heart defects floating menu with animated normal heart.

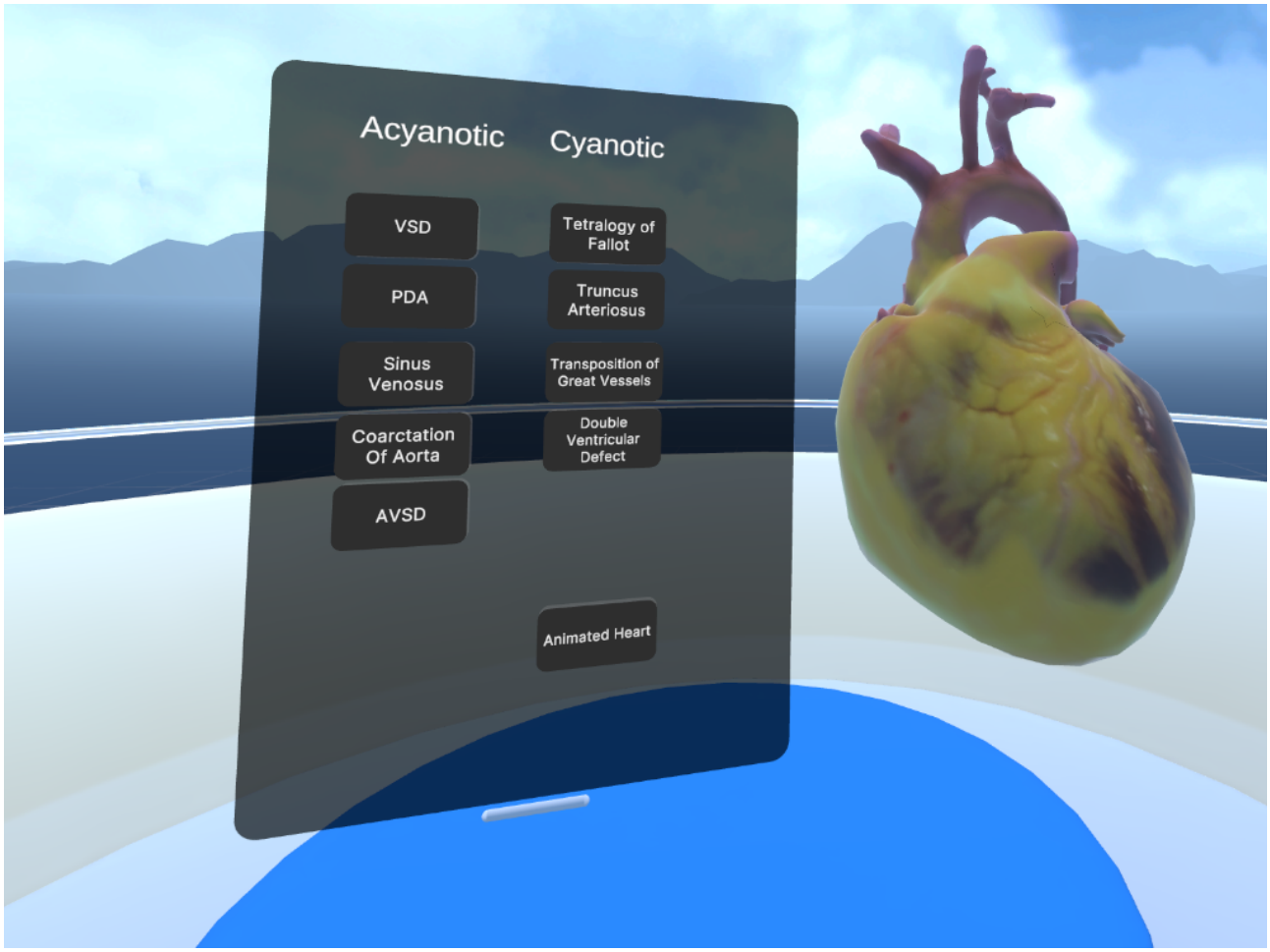

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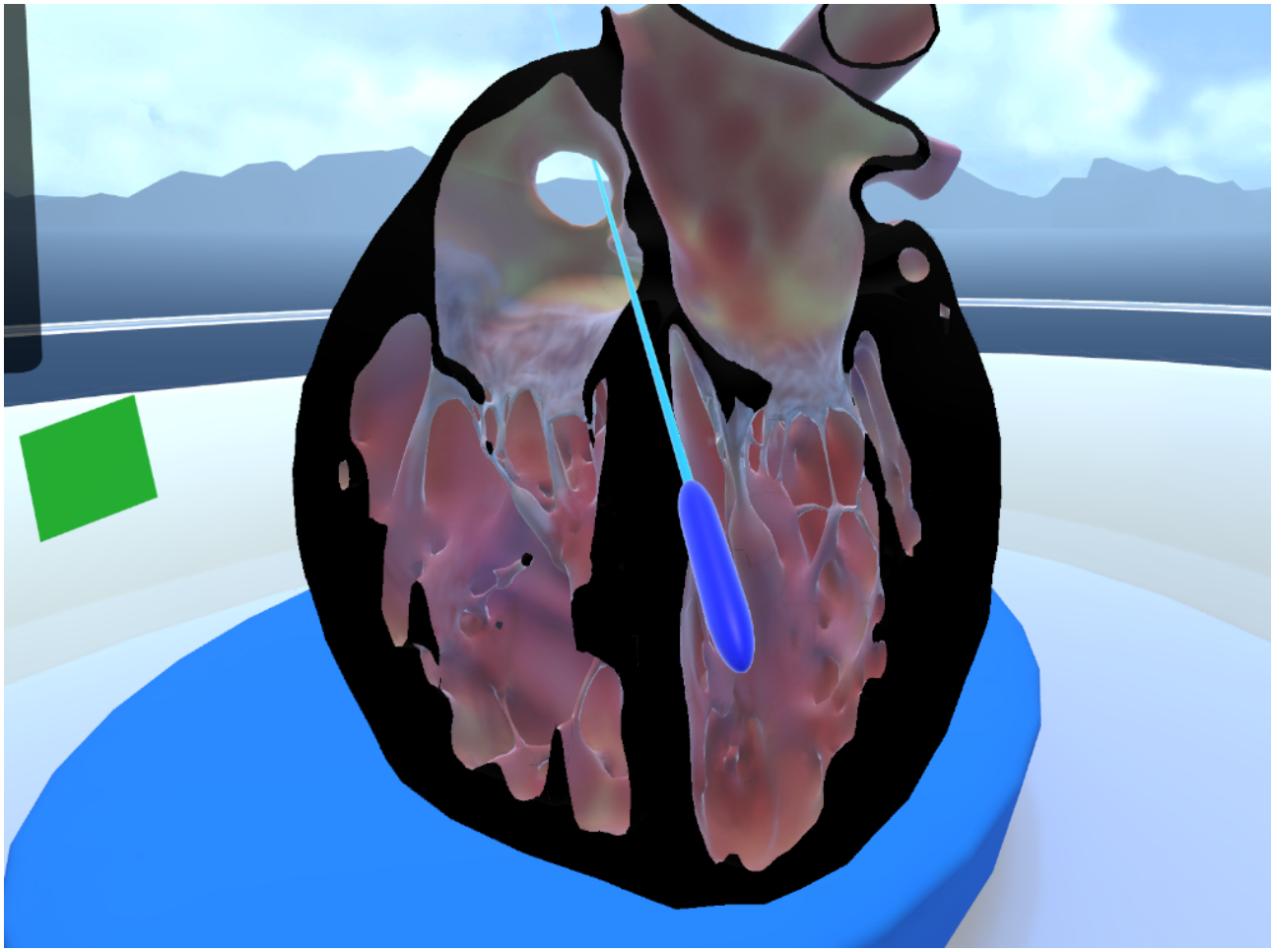
Figure 2. Pointer and cutting plane tools for this virtual reality application.



Multiple users can also freely interact with a heart with normal anatomy, which is animated to visualize how different structures of a normal heart, such as valves and myocardial walls, interact during the cardiac cycle of systole and diastole. Additionally, users can interact with various pathological models adapted from real tomographies, such as: for noncyanotic heart defects, a ventricular septal defect, a sinus venosus type atrial septal defect, a patent ductus arteriosus, an atrioventricular septal defect, a coarctation of the aorta, and for cyanotic heart defects, with truncus arteriosus, transposition of the great arteries, and tetralogy of Fallot (ToF) (Figure 3).

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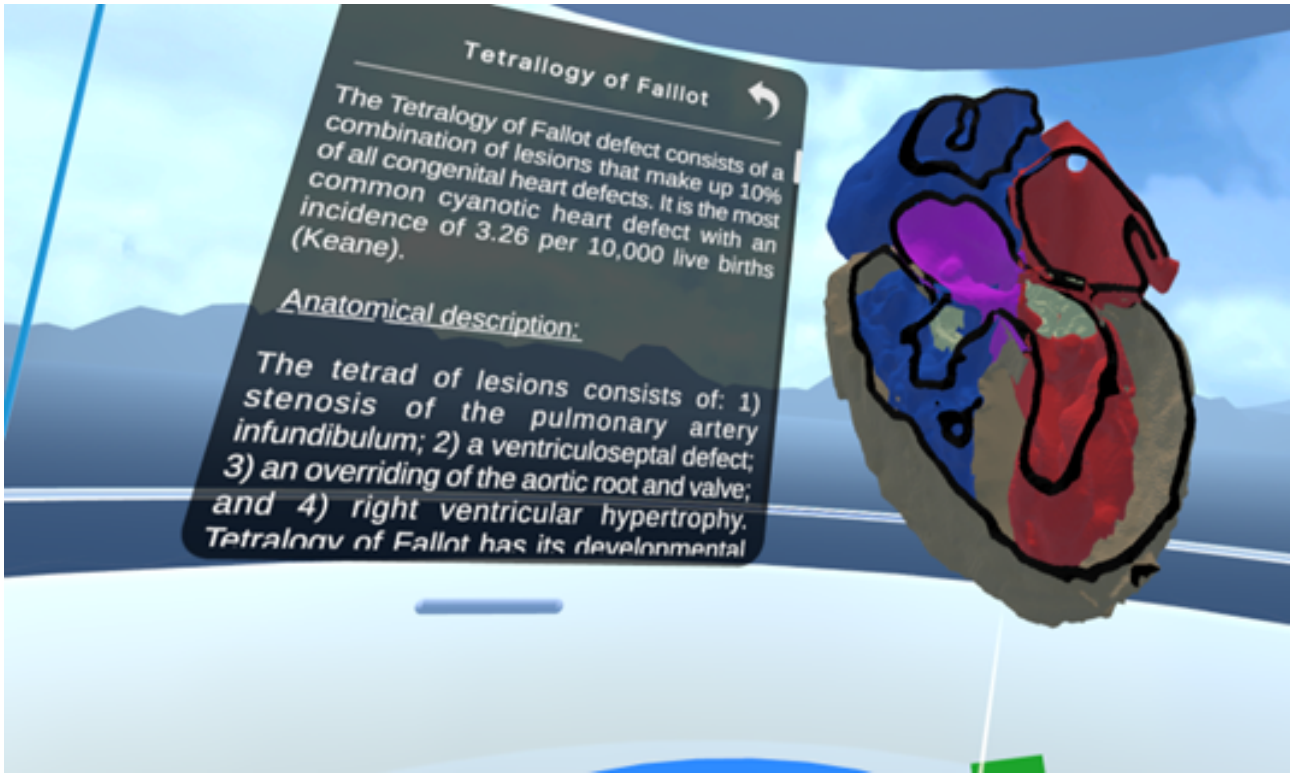
Figure 3. Tetralogy of Fallot heart model and description.



To facilitate collaborative teaching, a multiplayer architecture was implemented using Netcode for GameObjects, allowing synchronization of 3D models and actions across multiple devices in different global locations (Figure 4). This enables the use of a virtual classroom where the teacher has the abilities to instruct anatomy classes in real-time, point out defects with simultaneous visualizations by students, and guide anatomical tours, while students can access interactive menus and communicate with each other as well as the teacher for more immersive experiences.

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Figure 4. Collaborative multiplayer environment.

Participants and Intervention

To evaluate the functionalities of our newly developed application, this study utilized a cross-sectional observational design, it was conducted at the Visible Heart Laboratories (University of Minnesota, Minneapolis, USA). Data collection took place between 09/16/2025 to 09/20/2025.

The study used a convenience sampling method; a heterogeneous group of experts in cardiology, biomedical engineers, and medical trainees who visit our facilities for training on cardiology procedures and research purposes were invited to participate in our pilot study. Participants were provided with an Information Sheet for Research outlining the study procedures. Given that no Protected Health Information was being collected, the Information Sheet for Research provided before the data collection served as an Informed Consent process. Note, all participation was voluntary, and no incentives were given (Multimedia Appendix 1).

Users were asked to try the VR tool in person after having received detailed instructions on how to use the educational tool. After that, it was required for the participants to select a given CHD, manipulate a VR heart, and find where the defect is located, slicing the heart with a virtual multiplanar cut, to identify the specific defect within the heart in different points of view. Participants were given the opportunity to freely interact with the VR environment for 15 minutes. After the VR intervention. Finally, after the intervention, participants completed a professional background and a 23-item training satisfaction survey. Survey responses were collected via an electronic form; these were filled out with a personal device. Data were collected anonymously using online Google Forms (Google LLC).

The sample size was determined by the availability of eligible participants visiting the laboratory during the data collection window. To minimize recall bias, the survey was administered immediately after the VR experience. Selection bias is acknowledged due to the convenience sampling of individuals already present in a specialized cardiac research center.

Collection Instruments

A QR code was provided to answer the survey in which we gathered information related to *Professional background:* Professional role, years of experience in the field, experience with VR, experience with CHD education; and *VR-application satisfaction survey* that was assessed using a Likert survey adapted from the previously validated System Usability Scale [33] and a validated measure of VR user experience [34], also some other additional satisfaction questions about educational challenges on CHD education, VR application evaluation and implementation feasibility, also some open-ended questions were given for qualitative feedback. All responses were collected in an unidentifiable manner on a Google Forms spreadsheet (Multimedia Appendices 1-3).

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Statistical Analysis

Anonymized raw data were exported from Google Forms into Microsoft Excel for data organization. All statistical analysis was performed using Python (version 3.10) with Pandas and SciPy libraries. Descriptive statistics were conducted for all variables; categorical variables were reported as frequencies and percentages (n, %), whereas continuous variables were expressed as mean (SD) values, with 95% CI.

To determine the primary hypothesis regarding the application utility versus traditional methods effectiveness, a Wilcoxon signed-rank test was used to compare the responses within the same subjects (this test was selected due to sample size, N=9). One-sample Wilcoxon signed-rank tests were used to determine statistically significant responses different from neutral (score=3). Statistical significance was defined as a two-tailed *P* value <.05.

Ethical Considerations

The protocol of this study follows ethical guidelines of the 1975 Declaration of Helsinki, ensuring compliance with international standards for the ethical use of human data in research and was reviewed and approved by the IRB #CEIC-0074‑2022 by Hospital LaCardio (Bogota, Colombia), and by the IRB #MOD00055981 (Atlas of Human Cardiac Anatomy: pediatric heart defects) at the University of Minnesota (Minneapolis, MN, USA). The medical images used in this study were originally obtained for clinical and educational purposes, with informed consent secured from patients at the time of imaging for educational and research uses. Following their initial clinical use, associated images were anonymized to ensure patient confidentiality. No additional consent was required during the development of this study, as the anonymized data posed no risks to patient privacy.

Results

Background Information

A total of 9 participants completed the survey, in which 4 (44%) were cardiologists, 2 (22%) were medical trainees, 1(11%) a biomedical engineer PhD student, 1 (11%) a biomedical engineer faculty member, and 1 (11%) a cardiac researcher. Respondents reported a wide spectrum of VR familiarity, from no prior experience to regular users, with 1 person having more than 20 years of experience, 1 user having between 11‑20 years of experience, 2 users between 6‑10 years of experience, 4 users having between 2‑5 years of experience and 1 person having less than 2 years of experience in their respective fields. Of those, 5 users described themselves as being “moderately familiar” with the use of VR, 1 user self-described as “very familiar,” and 3 users self-described as being “expert level” (See Table 1).

Table . Participants characteristics.

Characteristics and Category	Participants (N=9), n (%)
Professional role	
Pediatric cardiologist	3 (33.30)
Medical student/Resident	2 (22.20)
Adult CHD[a] cardiologist	1 (11.10)
Cardiac researcher	1 (11.10)
Bioengineering faculty	1 (11.10)
BME PhD student	1 (11.10)
Years of experience	
2‑5 years	4 (44.40)
6‑10 years	2 (22.20)
<2 years	1 (11.10)
11‑20 years	1 (11.10)
>20 years	1 (11.10)
Prior VR[b] experience	
Moderate (used several apps)	4 (44.40)
Extensive/Expert	2 (22.20)
Limited/None	3 (33.30)

[a]CHD: congenital heart defect.
[b]VR: virtual reality.

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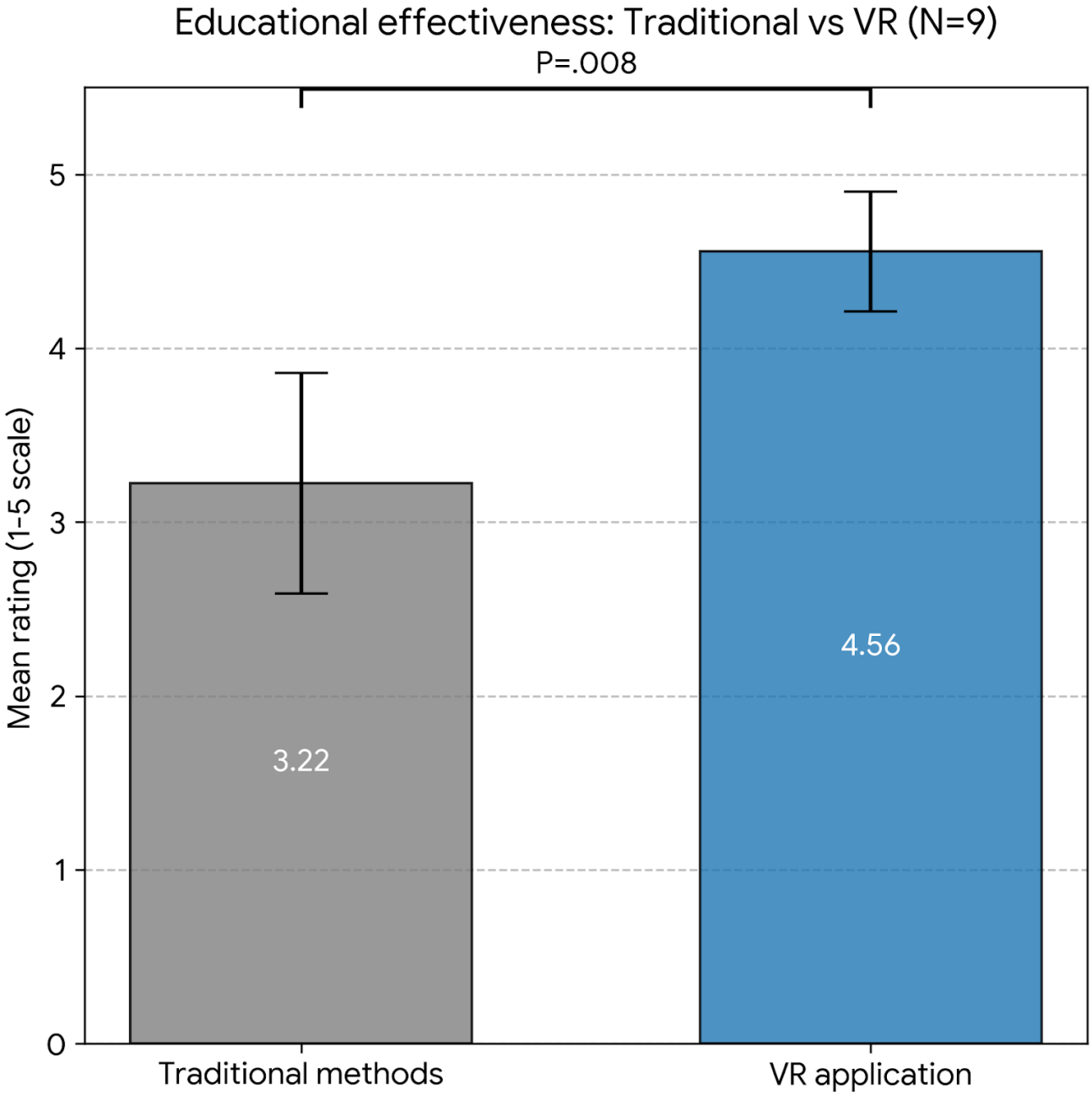
Perceived Effectiveness: VR vs Traditional Methods

Participants rated their perception of potential educational value for the VR app higher with a mean of 4.56 (SD 0.53), than traditional methods' effectiveness with a mean of 3.22 (SD 0.97), with a significant statistical difference (*P*=.008), using a Wilcoxon signed rank-test (See Figure 5).

Figure 5. Perceived effectiveness of VR-based education versus traditional methods. VR: virtual reality.



Perceived Suitability in Different Educational Contexts

Participants evaluated the application's suitability for various target audiences given its educational content; they rated the application suitable for medical students at preclinical and clinical years, (mean 3.22, *P*=.02) and for patient education (mean 4.11, *P*=.03). Participants were likely to recommend the application (mean 4.44, SD=0.73, *P*=.009). Ratings for anatomical accuracy (mean 3.88) and suitability for practicing physicians (mean 4.11) were positive but not statistically significant. (See Table 2 and Figure 6).

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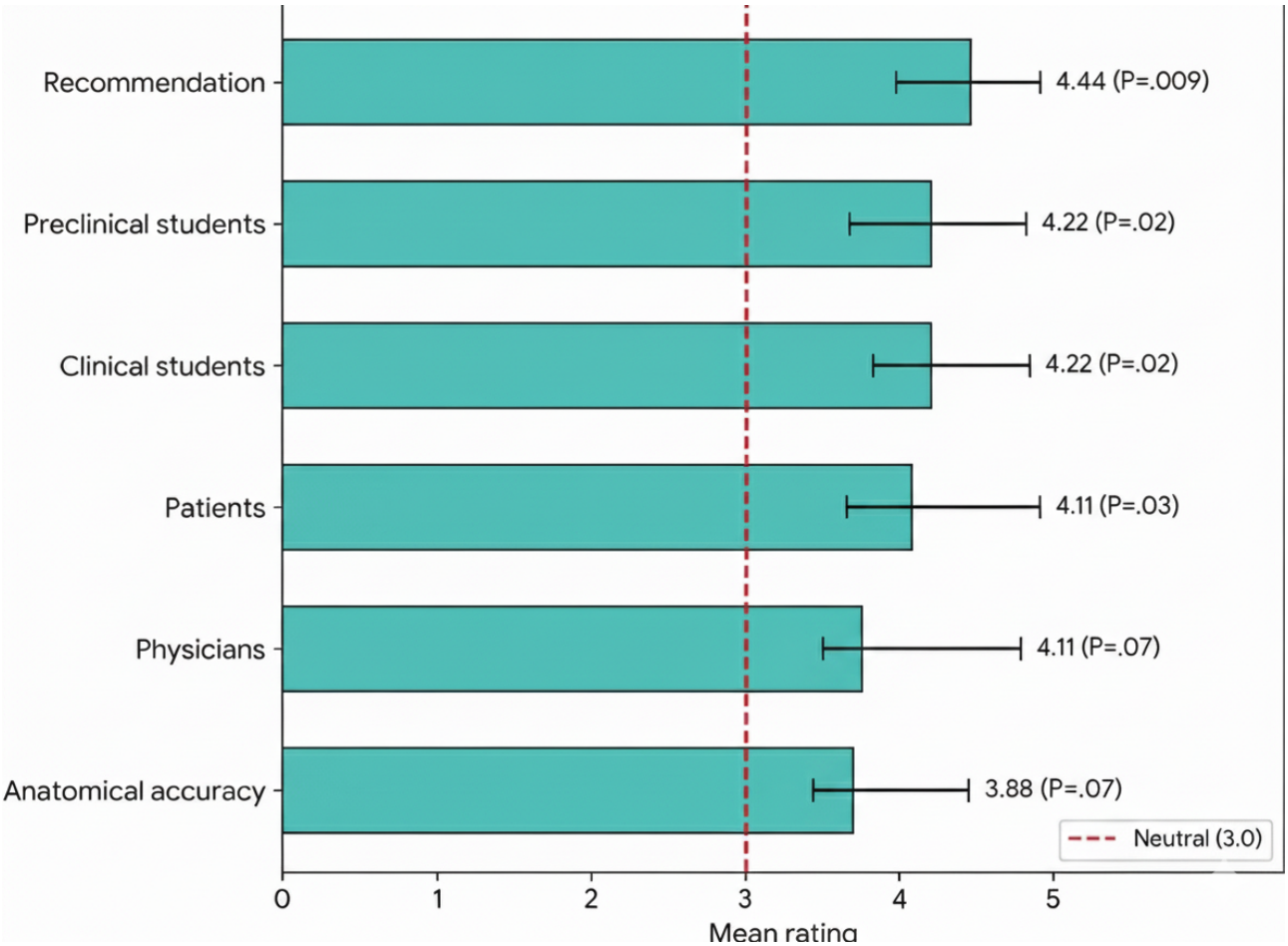
Table . Perceived effectiveness and suitability of VR-based[a] education for congenital heart defect.

Survey item	Mean (SD)	*P* value
Primary comparison		
Traditional methods effectiveness	3.22 (0.97)	Ref
VR application educational value	4.56 (0.53)	.008
Suitability		
Likelihood to recommend	4.44 (0.73)	.009
Suitability: Preclinical students	4.22 (0.83)	.012
Suitability: Clinical students	4.22 (0.83)	.012
Suitability: Patient education	4.11 (1.05)	.03
Suitability: Practicing physicians	4.11 (1.27)	.07
Anatomical accuracy	3.88 (1.13)	.07

[a]VR: virtual reality.

Figure 6. Perceived suitability for educational contexts.



Usability and Feasibility

It should be noted that the main significant challenges of CHD education, recognized by the users, were related to the complexities of the 3D spatial relationships recognized by 9 out of 9 (100%) of users, as well as the lack of interactive learning tools 6 (66%), and the limited availability of specimens and cases 3 (33%). The ongoing educational methods most commonly used by the users for CHD education were 2D illustrations/textbooks 9 (100%), followed by PowerPoint presentations 8 (88%) and clinical cases or rotations 4 (44%). Most users agreed that one of the most innovative features of our developed VR application was having real high-resolution CT scan-based 3D models 9 (100%) and real-time multiplanar cutting tool 7 (77%). Regarding the relative accuracies of the models, 3 (33%) of the respondents noted that they were found to be extremely accurate, 2 (22%) thought that they were very

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accurate, 2 (22%) noted that they were moderately accurate, and 1 (11%) considered them slightly accurate.

Regarding the feasibility of implementing these CHD learning tools, the most noted concerns for this VR application were technical complexity for users 6 (66%), 2 (22%) of individuals thought that the models needed to be more moderately accurate, and most felt that the costs of VR hardware 6 (66%) were a barrier. Also, 6 (66%) of users noted that one of the most critical barriers for ultimately implementing this VR tool at their institution would be related to budget constraints. When we asked the question, what additional features would enhance the educational value of this VR application, 6 (66%) of the users recommended adding post-surgical procedural simulations, while 5 (55%) recommended built-in assessment/quiz tools. Others noted that haptic feedback capabilities and additional cardiac pathologies would also be of value.

Qualitative Feedback

For the obtained feedback on the open-ended questions, a large majority of users praised the CHD VR application's ability to visualize complex 3D anatomy and their relationships with associated defects. Most respondents commonly mentioned that the benefit was improving anatomical understanding. Users noted:

> *It offers a lot better 3D understanding of the anatomy.*

and

> *It can help better visualize 3D interactions and gather people without geographical constraints.*

Yet it should be noted that the participants most commonly recommended adding blood-flow simulations and improving user interfaces for collaboration, which would help guarantee that the user is able to follow the educational purpose of the app. One suggested:

> *Have better CHD models, be more intuitive, and have a set of cut hearts already. Also, adding blood flow through the defects would be very interesting.*

Others advised about the risks of losing face-to-face interactions:

> *Needs to guarantee that the student/patient is able to follow, we are losing the face-to-face interaction, and we would not be able to tell if they are following, listening, understanding, etc.*

Most of the common concerns about implementing such VR technology in the educational field were related to technical support, hardware costs, and continued maintenance, as well as educational institutions' resources. Users displayed reservations about:

> *Widespread implementation across places with different financial resources.*
>
> *The maintenance of VR systems and the longevity of the technology.*

Most respondents agreed that our CHD VR tool would be most effective in small group sessions, in self-directed learning, or within one-on-one patient interactions.

Discussion

Principal Findings

Our findings demonstrate that a VR application integrated with specific CHD models from real CT images is perceived of high educational value for CHD education, compared to traditional methods by a group of experts and trainees, consistent with previous literature [25,31]. While other similar applications exist [30,31], participants highlighted the integration of CT scans to generate a high fidelity heart model of great value (9 out of 9 participants, 100%), as well as the ability to perform multiplanar real-time sectioning on the heart models serving as a virtual dissecting platform to overcome physical constrains, such as, limited availability of specimens, noted by 3 out of 9 participants (33%).

Educational utility

Most survey respondents also agreed that small group sessions and an independent learning setting could be the main uses for this application, specifically for medical education training and patient education, which is consistent with previous systematic reviews and meta-analyses on XR and medical education on knowledge improvement [27,28]. Of interest, most suggested future features we should consider for future implementations should include: post-surgical procedure simulations, additional cardiac pathologies, progress tracking and quiz tools, multi-language support, as well as AI integration.

Thus, our work should contribute to the field of digital medical education by providing a reproducible framework for developing immersive cardiac simulators, while simultaneously addressing technical and pedagogical aspects. Note that, unlike commercial VR solutions, our approaches prioritize didactic customizations, facilitating curricular adaptations. Developed educational VR applications in general offer multiple advantages over traditional learning methods. Here, we discuss the ability to allow multiplayer visualization, real-time interactivity with complex cardiac structures, active and collective learning in a virtual classroom, and increased accessibility. These features require the use of VR, a valuable supplement to traditional education methods, potentially helping to reduce stress and anxiety for some students [10,27]; but some may induce undesired side effects.

Limitations

Despite its potential learning advantages, it is important to consider some limitations of VR use, which can cause adverse effects such as visually induced motion sickness or "cybersickness" that may negatively impact or even limit the uses of these learning experiences for some users [29,35]. Similar to what was described in other VR educational studies, even though users think that this is a good adjunctive tool that could be used for medical education, they also believe that potential drawbacks for this could be software and hardware maintenance issues. Additionally, the technological learning curves can vary from user to user, depending on their initial familiarity with controls and video game usage. Further, for some, implementation costs can also be a factor, including expenses associated with hardware, software, and human

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resources such as systems engineers, computer scientists, graphic designers, healthcare personnel, and researchers, among others [6]. We acknowledge that a potential novelty bias associated with VR educational technologies should be acknowledged by lessening the educational outcomes of subjects interacting with new technologies for the first time [36]. The use of convenience sampling with the participants of different activities at a cardiovascular laboratory means that participants will have higher knowledge and/or interest in cardiovascular VR applications, which poses one of the greatest limitations of this study. It is important to note that a small sample size limits the statistical power and generalizability of the study.

Future directions

Furthermore, long-term comparative controlled clinical studies should be designed and performed associated with our developed VR platform, to assess knowledge retention in students and/or patients with congenital heart diseases. It is also important to consider other ethical implications of using VR of real patient anatomy in medical education. Additionally, the costs of such technologies could, in part, create educational inequalities in regions with fewer economic resources. Finally, it is essential to ensure that students do not develop an excessive dependence on VR, neglecting other essential practical skills such as direct tissue manipulations and/or dissections.

Conclusions

This framework portrays the integration of an innovative VR application with high-fidelity CT scans of Congenital Heart Defects as a potential tool for medical and patient education. Our findings suggest that VR could be easily implemented and adapted by medical educators to bridge the cognitive gap in understanding complex defects. This work also serves as a stepping stone into a more advanced and technological approach for education using newer tools like AI or XR as educational tools for medical curricula. Furthermore, its ongoing development and continuous collaboration between multiple research centers and academic institutions could have a substantial impact on the training of future healthcare professionals and on patient education. The VR platform we described here could help all types of learners better understand CHDs, provide a means for clinicians around the world to discuss complex CHD and treatment approaches, and aid medical device designers relative to future innovations.

Acknowledgments

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The authors declare the use of generative AI (GAI) in the research and writing process. According to the GAIDeT (Generative Artificial Intelligence Delegation Taxonomy, 2025), the following tasks were delegated to GAI tools under full human supervision: Proofreading and editing.

The GAI tool used was: Grammarly.

Responsibility for the final manuscript lies entirely with the authors.

GAI tools are not listed as authors and do not bear responsibility for the final outcomes.

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Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Authors' Contributions

KM: Investigation (lead), methodology (lead), writing – original draft (lead). DB: software (lead), writing – review & editing (supporting). CG: conceptualization (equal), Project Administration (lead), Supervision (lead). SN: conceptualization (equal). PAI: conceptualization(equal), Supervision (equal), Funding Acquisition (equal).

Conflicts of Interest

The authors associated with the Visible Heart Laboratory (VHL) declare a non-financial conflict of interest (COI) in that they were directly involved in the design and development of the Virtual Reality application that is the subject of this evaluation study. This COI is being disclosed to ensure transparency regarding the authors' foundational role in the technology being assessed. All other authors report no financial or non-financial conflicts of interest.

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Multimedia Appendix 1
Information sheet.
[DOCX File, 17 KB - xr_v2i1e74429_app1.docx]

Multimedia Appendix 2
Implementation survey.
[DOCX File, 19 KB - xr_v2i1e74429_app2.docx]

Multimedia Appendix 3
Virtual Reality app implementation survey (Likert Style Table).
[XLSX File, 73 KB - xr_v2i1e74429_app3.xlsx]

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Abbreviations

AR: augmented reality
CHD: congenital heart defects
CHD: congenital heart defects
CT: computed tomography
GAI: generative artificial intelligence
VIMS: visually induced motion sickness
VR: virtual reality
XR: extended reality

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Role of Augmented Reality in Tertiary Care: Qualitative Investigation Using Thematic Analysis

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Abstract

Background: While augmented reality (AR) as a concept is not new, it is still an emerging technology with a wide range of applications that it could provide value for. In the medical field, AR is becoming ever more prevalent, but while it has been applied to various medical tasks, it is far from commonplace. Radiological imaging has been suggested as one of these applications, and the radiology workflow capacity crisis the United Kingdom's National Health Service is experiencing is a potential opportunity for technology to alleviate pressure. Understanding clinical stakeholders and current systems is important for identifying design opportunities for developing AR to enhance interactions and gain more from radiological images.

Objective: This study had 3 key aims. First, to build an understanding of the field in the context of AR; second, to understand the stakeholders and workflows surrounding radiological images; and finally, to suggest how AR could integrate within these workflows and current practices in order to provide value.

Methods: We conducted 14 interviews with hospital-based consultants in a range of specialties and then completed a thematic analysis on the transcripts in order to find trends that suggest what value AR could add to radiological imaging, where that value could be added, and who would benefit. We implemented reflexive thematic analysis to develop themes from across the interviews, which were then built on to suggest design implications.

Results: We find that the need for efficiency in image evaluation is present across many roles, regardless of the clinical question, but consultants can be resistant to new technology. Additionally, we find that the current capability of AR technology could be of greater benefit to radiologists as opposed to surgeons or other practitioners. We discuss these findings for the development of AR applications and present 3 design implications that stand as our core contribution.

Conclusions: We conclude with 3 design implications for the application of AR within radiological imaging based on the results of our thematic analysis and frame them within the Human-Computer Interaction and medical fields. The first design implication highlights efficiency and how AR has the potential to allow for quicker comprehension and measurements. Second, we suggest that the capability of AR tools should complement existing techniques and not simply replicate current ability in 3 dimensions. Finally, the integration of AR tools with existing workflows is crucial in the uptake of the technology in order not to negatively disrupt practice.

(JMIR XR Spatial Comput 2025;2:e68810) doi:10.2196/68810

KEYWORDS

augmented reality; clinical practice; radiology; surgery; thematic analysis

Introduction

Overview

Augmented reality (AR) for clinical use was first mentioned in 1982 [1] and 1992 with a head-mounted display (HMD) [2]. Using AR in a clinical setting is not a new concept, but it is still in relative infancy [3,4] with many suggestions as to the specific applications [4-6]. It is a promising application area of AR with many examples presented [7]. Despite this, it is still an emerging technology, and there is very little uptake of AR in the day-to-day of clinical practice [6]. The motivation of this study is to explore where this emerging technology could provide value to modern medical practices, specifically radiological imaging. The Royal College of Radiologists highlights the urgent workflow capacity crisis in terms of the number of staff not keeping pace with the increasing demand for imaging. Increased strain is therefore placed on existing staff within the National Health Service (NHS), the publicly funded health care system in the United Kingdom [8]. By exploring these problems

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in the context of AR, we can begin to understand how the technology could fit into the goals or requirements that are present in today's practice, such as increased efficiency or higher accuracy.

In this study, we conducted an interview study to investigate the current clinical landscape of radiological imaging in modern medicine to better understand the potential roles AR could play and the value it could bring. This was achieved by conducting a set of interviews with consultants in different tertiary care specialisms (highly specialized care) aimed at exploring the current practices and perspectives of professionals who work with radiological images, in the context of using AR technology. As a result, we propose 3 design implications to consider when designing AR systems for clinical use, which stand as our core contribution. Our design implications were informed by experiential accounts and opinions regarding what radiological images are used for, how they are used, and what stakeholders gain from them. We recruited surgeons and radiologists as key stakeholders, and a focus was put on the interactions these stakeholders had with the images used during clinical workflows. This enabled us to examine the contents of the interactions as well as the users' experiences and opinions on how successful they were in the context of looking for opportunities to design for AR. The current tools used, how the tools are integrated into practice, and opinions on them were also considered.

The aim of these interviews was threefold: to gain an understanding of the field in the context of this technology, to gain an understanding of the stakeholders and workflows surrounding medical images, and to begin to understand the role that AR could play within these workflows. The interviews were semistructured around questions that sought to clarify medical facts, explore the opinions and discrepancies of current practice, while also probing attitudes toward the problems, opportunities, and new technologies that are faced. The interviews have been analyzed using reflexive thematic analysis [9,10] to understand trends and contradictions across the data set. This analysis is intended to understand what value AR could provide in a clinical environment and, therefore, identify application and interaction design opportunities and suggest some design implications. Going forward, this will allow us to begin to identify some of the needs of tertiary care practitioners in the context of this technology. The contribution of this work is the empirical understanding gained through the thematic analysis and the 3 design implications developed based on this analysis. The thematic analysis aims to understand the needs and challenges experienced by hospital-based consultants, and the design implications are developed through and justified by this thematic analysis.

Background

Development of AR

AR superimposes digital objects into the users' view in real-time using a headset or other device. The aim is to add virtual components to the user's field of view to provide them with additional information while carrying out a task [5]. Although the term was coined in 1992 [11], the technology has seen a boom in interest in recent years [12]. It was at this early stage in 1992 that AR would be suggested as a tool to aid surgery by Rosenburg [2]. Rosenburg suggested that just as a physical ruler can be used as a tool to aid in drawing a straight line on a piece of paper, AR could be used to guide surgeons' incisions, and that AR would be better than any physical tool for this task as the virtual components could be partially submerged in the anatomy to strictly follow key lines and boundaries.

Since this time, AR technology has developed with advancements such as viable HMDs, allowing wider and more creative adoption [13]. There is little clinical use of AR, but interest in the technology for use in this space is growing [6]. It has been suggested for image-guided surgery (IGS), as Rosenburg did, but also for tasks such as medical training, clinical psychology, diagnostics, surgical planning, and rehabilitation [5,14,15].

HMDs are the dominant way of using AR, and technological developments have meant that they can display content accurately enough to enable convincing interactions. However, technological and usability issues persist around AR HMDs [16-18], with the effectiveness and accuracy of AR in many clinical tasks difficult to validate and therefore remaining to be proven [19,20]. A key set of issues documented across a variety of AR headsets is the perceptual inaccuracies and issues that can arise. Perceptual issues are an important area of research, as regardless of the domain or individual application, an otherwise perfect AR experience could be made intolerable by physical symptoms as a result of inaccurate perceptual cues. This is particularly true in a medical environment where the accuracy of the tools used can have an implication on a patient's life [21].

Poor perceptual cues can place stress on a user, resulting in symptoms such as motion sickness, nausea, and visual fatigue. Focal rivalry is a common example of inaccurately represented virtual content, placing unmanageable stress on the users' vision. Focal rivalry is where the eyes cannot focus on 2 objects at different depths at the same time and therefore have to switch between focusing on the physical object and the virtual, a requirement rarely seen in the natural environment [22] .

The vengeance-accommodation conflict is another common perceptual issue that has been documented to cause physical symptoms. The vengeance-accommodation conflict [23] is caused by the eye's 2 mechanisms of focusing competing against one another. Most modern HMDs have a fixed focal depth of around 2 m, but as virtual content is moved away from this plane, inaccurate depth cues are created, often out of the bounds of what a user's eyes can tolerate [24].

Gold Standard: AR IGS

AR IGS was one of the first clinical applications AR was suggested for, and is still a key area of interest in medical AR research, and is a clear application of the technology [19]. It can be argued that AR IGS is the gold standard of clinical AR as there is broad agreement that having live guidance for operations would be of significant value to the surgeon, resulting in a higher chance of successful surgery [15,25,26]. The theoretical implementation of IGS is that guides such as 3D virtual representations of anatomy, built from preoperative

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scans, are overlaid onto the patient in order to allow the surgeon to see anatomy below the surface and more easily identify structures, as well as the boundaries between them. This is intended to speed up procedures, reduce trauma, and reduce recovery time [27].

However, significant issues remain with reaching this goal, which can be broadly divided into technical and usability issues. An important technical issue is registration, the process of aligning virtual components with their physical counterpart. Registration requires enough identifiable points, which can be known as markers, to be present on both the virtual object and the physical anatomy in order to map one to the other, and in a lot of cases, there are not enough. Machine learning algorithms have been used to approach this problem and generate nets of points across both objects, then map them together [28]. Bertolo et al [29] cite registration as a prominent unsolved challenge and state that in the era of "precision surgery," clinicians will expect error margins to be negligible.

In addition to the technical issues, it is still unclear how best to present virtual content to a surgeon for IGS. Dilley et al [30] suggest that even with perfect registration, surgical performance is reduced when virtual content is overlaid onto the surgical site. Their work suggests that even in a currently fictional environment where perfect registration can be achieved, projecting the images used for guidance beside the patient, unregistered, provides a better outcome.

Determining the best way to present virtual content is one of many usability issues that remain unsolved. Successfully determining what virtual content is best to display to a surgeon can only be useful if the methods the surgeon uses to interact with the content are intuitive, unobtrusive, and effective. The study by Eddie [19] suggests that the visualization and interaction challenges are the biggest challenges facing AR surgical guidance.

AR IGS is likely to provide significant value to surgeons once its value and accuracy can be proven. However, there are multiple issues that all need to be overcome to achieve this. IGS is far from the only application of clinical AR to provide value [31].

Modern Clinical Applications

Modern clinical applications of AR can broadly be split into 3 categories: intraoperative (eg, AR IGS discussed above), education and training, and presurgery tasks. The educational and training applications of AR are very broad, ranging from using AR to facilitate the learning of anatomy to safer, more repeatable surgical training [32]. AR has the potential to provide more immersive, repeatable, readily available training and education in the medical field, allowing everyone from medical students to qualified surgeons to take in new knowledge in a new way [4]. In situations where a qualified surgeon is learning a new procedure, AR allows a safer, no-pressure environment for the surgeon to understand how the procedure works and repeatedly practice the intricacies [33].

There are several applications of AR in the presurgery domain, principally, diagnostics and surgical planning. AR for surgical planning allows the surgeon to view preoperative images such as computed tomography (CT) and magnetic resonance imaging (MRI) images, as 3D models of the surgical site before the procedure [15,34]. This is suggested to allow the surgeon to gain a better understanding of the surgical site and relationships between structures, meaning they can plan how a procedure will be approached and be more prepared for potential complications [35].

Douglas et al [36] suggest that using AR could improve diagnostic accuracy and speed up the diagnostic process when viewing cross-sectional images such as CT and MRI. Pelargos et al [37] state that "surgical planning is inherently a 3D task" and that virtual reality and AR technologies could help by improving the understanding of the complex anatomical relationships. These tools have the potential to offer better visualization of areas of interest and therefore improve the understanding and the speed at which decisions can be made [34,38]. Trestioreanu et al [39] argue that AR and virtual reality have the potential to improve radiology health care by improving the cognitive experience, by reducing the cognitive load that a clinician undergoes when viewing 2D slices of 3D anatomy. They go on to suggest that while a few 3D visualization methods currently exist, they do not offer the increased practicality or ergonomics that AR approaches could offer.

As it stands, there is very little AR in day-to-day clinical practice [6,19]. The literature discussed above has directed our work to focus on investigating where AR could be applied in the presurgical domain around radiological images and what value the technology could bring. This is a promising area of research where AR technology could be harnessed effectively. Our work is positioned to direct future research and contributes to the body of literature directing the development of AR applications for radiology, based on expert end user experiences.

Methods

Ethical Considerations

This work was granted ethical approval by Newcastle University ethics committee (27432/2022). Participants gave their informed consent to the interviews, and it was made clear that they could withdraw their participation at any time. Ages of participants were captured as ranges and demographic information captured was kept to a minimum to maintain participant privacy. Participants received no compensation for their time.

Recruitment Process and Participants

For this study, 14 semistructured interviews were conducted with medical professionals from a range of specialties to enable us to determine how practices and perspectives around radiological images vary across specialisms and hospitals. Five of these interviews were with radiologists with various subspecialties, while the remaining 9 were with other consultants in areas such as cardiology, cardiothoracic surgery, general surgery, orthopedic surgery, and clinical oncology. Participant demographic details are summarized in Table 1. All of the participants were male, which is acknowledged and discussed in the Limitations section. Demographic questions were voluntary, and as such, some participants chose not to share some personal information, which is denoted in Table 1 with

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"—." The participants worked at 8 different hospitals, 5 of which were in the Northeast and Northwest of England. Two of the remaining were London hospitals, and one on the South coast of England. Initial participants were recruited through the authors' host university medical school via public staff lists. These participants were then asked to refer other potential participants, especially from other hospitals and regions of the United Kingdom, having a snowballing effect. One of the participants was previously known to the researchers, 2 participants were recruited through mutual acquaintances, and all others were previously unknown to the researchers.

Table . Participant demographic information.

ID	Age range (years)	Ethnicity	Role	Time in current role
A	45 - 54	White British	Consultant interventional cardiologist	19 years
B	45 - 54	Mixed White Asian	Consultant cardiologist	11 years
C	45 - 54	Indian	Consultant cardiologist	14 years
D	__[a]	—	Consultant oncologist	—
E	55 - 64	White British	Cardiac surgeon	20 years
F	55 - 64	—	Consultant interventional and diagnostic neuroradiologist	—
G	45 - 54	White British	Thoracic surgeon	11 years
H	—	—	Orthopedic surgeon	—
I	45 - 54	White	Consultant general surgeon	10 years
J	55 - 64	White British	Cardiothoracic surgeon	5 years
K	25 - 34	Mixed White Arab	Consultant neuroradiologist	9 months
L	35 - 44	White British	Consultant radiologist (nuclear medicine)	10 years
M	35 - 44	Indian	Consultant radiologist	4 years
N	35 - 44	White British	Consultant cardiothoracic radiologist	4 years

[a]Not available.

Interview Process

Semistructured interviews were chosen over fully structured interviews in order to be more open-ended and allow greater flexibility for free conversation. The interviews were all conducted over Microsoft Teams (Microsoft Corp) and lasted between 30 minutes and an hour. Fourteen questions were drawn up based on prior reading in the area, in context with the aims of the interviews. The first objective of the interviews was to act as a means of gaining knowledge of relevant medical specialisms, their current working practices, and collaboration methods across NHS trusts. This way, the authors could build a solid base of knowledge of the field that allowed an appreciation of the context and the identification of nuance in practice. The current practice surrounding radiological images was a key point here. This included establishing how images are used, the tools used to interact with them, how the tools and requirements change between different specialties, and what is gained from the images themselves, that is, what questions they are used to answer. This continued into establishing the current workflows around these images, the communication between stakeholders in reference to imaging, particularly the communication between these hospital-based consultants, how information flows between stakeholders, and what this process looks like from a patient's perspective.

The clarification of this base knowledge laid the groundwork for more in-depth questions exploring the opinions around these areas: how useful the tools are, how the tools vary, and how personal preference influences both the use of tools and the practice itself. This was then followed by questions about their experience level, their use, and the utility of AR, which were intended to explore the current uptake of this technology and opinions on AR as it exists at the current point. Finally, there were questions about the future of the participant's specialty and what technologies they saw as having a notable impact.

Analysis Process

Overview

The interviews were recorded and transcribed, providing 14 transcripts that could then be subjected to reflexive thematic analysis. This allowed the authors to establish trends and reveal insights across the whole interview dataset. Thematic analysis is a set of methods for data analysis to develop, analyze, and interpret patterns across a qualitative dataset. Reflexive thematic

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analysis, developed by Braun and Clarke [40], is an interpretive qualitative approach that encourages critical reflection of the role the researcher plays in the analytic process and their research practice. Braun and Clarke talk about the inherent presence and necessity of biases and how they are integral to reflexive thematic analysis. Reflexivity is integral to this analysis method, "We must question why we think what we think. Bias, prior knowledge and who we are shapes subjectivity" [41]. Thematic analysis is a set of interpretive qualitative analysis methods, and as such, the researchers' perspectives and biases are used as tools for analysis. It is important to understand these biases when carrying out this form of analysis in order to understand the context used to come to conclusions and how that context influences the conclusions. It is at this point that we, as authors, must consider our positionality.

Positionality Statement

We cannot expect the interviews to uncover the full range of opinions and practices within a particular medical specialization, but we aim to include a sufficient range of participants in order to be representative of the area. Where this is not possible, the researchers acknowledge which groups could not be recruited and the effect this may have on the analysis. Authors 1 and 2 (JH and CB), who conducted the analysis, are computer scientists in Open Lab, a Human-Computer Interaction (HCI) laboratory in the School of Computing at Newcastle University, United Kingdom, with experience in digital health, but no formal medical training. Our expertise lies in qualitative methods and designing technologies for specialist user groups. The remaining authors contributed and provided additional context after the analysis was completed. These authors can be considered tech-savvy and protechnological innovation, which will lend the interpretations of the analysis to following this philosophy. Other researchers will bring different perspectives and have different experiences informing their analysis and will, therefore, come to different conclusions.

Implementing Reflexive Thematic Analysis

Thematic analysis is an overarching term for a flexible set of methods designed to interrogate qualitative data. This study follows the updated version of reflexive thematic analysis by Braun and Clarke [10], which builds on their original work [40]. It is appropriate for this study as the aim of the analysis was to understand the common themes and contradictions across all 14 interviews in order to provide rich insights across a range of specialties [42]. A reflexive approach was applied to this study to foster an organic coding process and to use researcher subjectivity as a tool. This approach means that "themes cannot exist separately from the researcher—they are generated by the researcher through data engagement" [42] and is a direct result of researcher subjectivity being positively exploited. While thematic analysis is a theoretically flexible set of methods, it is important to understand the theoretical base and assumptions being brought to the analysis [9]. For this study, the authors approached the analysis from a relativist ontological position and used a constructionist epistemology. This means that the authors could explore the meaning from the participants in context and be directed by this, constructing meaning and evidence through the analysis. This is opposed to a more traditional realist postpositivist approach, where it is considered that a single objective truth exists within the data, and it is the researcher's job to find it [10,43].

As defined by Braun and Clarke [10], an inductive coding process was used in this study. This was to enable the focus to be put on the participants' experiences and opinions, and as such, allow themes and contradictions between participants to be brought to the surface. As previously mentioned, this inductive process was colored by inherent epistemological and ontological assumptions as "you cannot enter a theoretical vacuum when doing TA" [44]. In a similar vein, a combination of both semantic and latent codes was used throughout the coding process. The semantic codes captured the explicit, surface-level detail that was being communicated while the latent codes grasped the deeper, more implicit points being made. This combination allowed for a thorough and meaningful analysis.

In terms of the analytic process, for reflexive thematic analysis, Braun and Clarke [10] detail 6 phases: familiarization, coding, initial theme generation, developing and reviewing themes, refining, defining and naming themes, and writing up. The familiarization phase was achieved in 2 ways, first, with the lead author conducting the interviews, there was an initial exposure to all of the data in the context it was given. Second, through the transcription process. Automated tools were used for the bulk of the transcription, but the lead author checked each transcript against the interview recording. This ensured that the transcripts were accurate while also contributing to the familiarization phase of the analysis. The coding and theme generation were primarily carried out by the lead author, with the second author offering opinions and challenging decisions after each round. Two full coding rounds were completed, and theme generation was completed over 3 iterations with the second author contributing opinions after the initial coding of 2 transcripts, again after all transcripts had been coded and between iterations of theme development. This contributed to the robustness of the coding and theme generation phases, as it was an opportunity for biases and assumptions to be questioned. The second author contributed to the analysis by reviewing initial codes and themes and probing into the reasoning behind them. This provoked further reflection on the codes and themes throughout the analysis process and meant that assumptions could be challenged, resulting in a deeper meaning being developed. Initial coding resulted in several hundred codes, but upon review, in between and after each coding round, similarities between codes were identified, and clustering codes together allowed for easier interpretation for theming. We then initially grouped codes into 12 broad patterns (eg, multidisciplinary teams [MDTs], personal preference, increased reliance on imaging, and relationships with imaging), which could then be reviewed between authors and the logic or biases challenged. These were then iterated on with the context and theoretical positioning discussed above to develop the themes presented below. Each theme articulates a different aspect of the conversations had while sitting within the context of this work.

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Results

Overview

The results are presented as the 4 themes developed through the thematic analysis process. These 4 themes are that communication is largely verbal or written, which acknowledges observations around how communication is conducted regarding radiological images and how it is mostly via the radiologists' report and in MDT meetings. Inconsistencies and personal preference in practice encapsulate the extent to which personal preference and other choices change practice. Extended reality (XR) maturity for surgery covers the opinions of current XR technology, AR in particular, and how there is potential for it in certain areas of practice, but there are still significant issues preventing the mass uptake. Finally, increased reliance on imaging is a known issue in radiology, but this theme explores the opinions in this area and the potential ramifications interviewees believe they will experience. These themes are summarized in Table 2.

Table . Theme table summarizing themes and characteristics.

Theme	Subthemes	Characteristics
Communication is largely verbal or written	• MDTs[a] • Written reports • An intuition of knowing what questions the next clinician will ask	MDTs and radiologists' written reports are stored and interacted with via PACS[b]. MDT communication is high-level, aiming to reach decisions quickly.
Inconsistencies and personal preference in practice	• Discrepancies in reporting • Discrepancies in tools used	Tools, expertise, and practice vary between consultants, departments, and trusts. Given the same tools, slightly different results are likely to be reached.
XR[c] maturity for surgery	—[d]	Current technological state of the art. The potential impact of AR[e] technology.
Increased reliance on imaging	• Efficiency required • Acceptability of new technology	Efficiency is a big concern for everyone, but particularly radiologists. The appeal of new technology to clinicians varies—value must be proven.

[a]MDT: multidisciplinary team.

[b]PACS: picture archiving and communications system.

[c]XR: extended reality.

[d]Not available.

[e]AR: augmented reality.

Communication Is Largely Verbal or Written

Including a variety of hospital-based consultants as participants in this study provided insight into the communication between these 2 parties and how radiological images are used in this process. Two of the important opportunities for communication in terms of radiological images are the radiologist's written report and the MDTs. The report written by the radiologist with their interpretation of the scan will aim to answer the clinical question that accompanies the scan and will be read by the referrer and any other consultant who has a stake in that patient's care. Any unrelated incidental findings will also be reported. For straightforward cases, this will be the only communication between the reporter and referrer; more complex cases are likely to be sent to an MDT. These MDTs will have at least one of every specialist relevant to the pathology present, and cases will be discussed as a group with each participant putting forward their views. It was made clear by participants that MDTs were introduced to help make better-informed decisions and to lift the responsibility of decisions from 1 person. Participant L described that these meetings aim to "make a good decision quickly."

The reports that accompany scans are the key value that radiologists contribute to the point where, for more straightforward cases, a referrer may not look at the images when planning the next step of the patient's care. Participant A said, "for most relatively simple questions, I would just go by the report."

The MDTs are the main point where cases are discussed and decisions are made with the full range of expertise. During these meetings, the radiologist will share relevant images and talk through the salient details with the group of specialists so that each can put forward their opinion. The images are not likely to be viewed for an extended period of time here, as MDTs are generally a high-level discussion, and there will be a lot of cases to get through in minimal time.

A trend across the interviews was the notion of knowing what information the next clinician in a patient's line of care will need in order to do their job, as well as the radiologist sculpting their report and the presentation of information at the MDT toward that. Participant L said, "I do the same MDT every week and have done for 10 years. So we're a bit more experienced [...] so that we know what they want in those specific circumstances." They then went on to talk about reporting scans from other hospitals and said, "If you don't know your referrers you don't know how they like their reports or whether there are specific things on there they want or things like that. So it's better to report scans from your hospital for a number of

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reasons.” There is the idea here that knowing, or having an intuition of the next steps of care, will have an impact on how information is portrayed.

Additionally, it is clear that while radiological images are essential to communicating information and making decisions for patients’ care, they play a supporting role and are only the center of attention to the radiologist reporting them. Each step after this, the radiologist distils the information down to the relevant points, chosen based on experience and specifically to answer relevant clinical questions.

Inconsistencies and Personal Preference in Practice

Overview

This theme encapsulates and describes the observed inconsistencies in practice between the range of specialists interviewed, and how much of a role personal preference plays in the details of practice. This is split into 2 subsections: reporting and tools.

Reporting

Across the dataset, particularly in the interviews with radiologists, the subjective nature of image analysis was made clear. Most of the radiologists used the term “interpretation.”Participant L said, “And my interpretation of it, if someone else has reported it, I will change if I don’t agree with it” in the context of reviewing cases before an MDT meeting. This subjectivity around the details of reporting presented itself directly through radiologists referencing it and also through radiologists talking about confirming others’ “opinions.”Participant L said, “when I’m allocated to do attending [...] we do get a lot of telephone calls asking for opinions from scans which have been done at other hospitals.” The data suggested that the uncertainty was greatest between departments or between hospitals. Participant N said, “if one of my colleagues has reported it [...] usually I just look at what they’ve said, because I’m always going to agree.” This suggests that within departments, experiences and expertise are shared and therefore create an isolated unit of consistency.

Radiologists also talked about sculpting their reports for those who were going to read them. The radiologist participants made it clear that in many cases, they know how specific consultants like their reports or that they know what questions such a consultant would have, and therefore, they write their report for them. This implies a level of inconsistency around what content should be in a report, and that efficiencies are gained by working with the same people for an extended period of time and getting to know how they work. Additionally, part of medical knowledge comes from the scenarios that individuals have experienced and the results of reactions to those scenarios. Participant N recalled 1 difference between him and a colleague who has recently retired was “He’s coming at it with far more experience and that will colour his opinions of all the things he’s seen and the things I haven’t seen. Likewise in certain areas I’ve trained for more recently than he has so some of the more modern things I might have done a little bit more of.” This experiential part of medical knowledge will likely lead to inconsistency in how scans are reported, as different reporters will bring different knowledge and experiences.

Tools

The use of different tools between different departments and trusts was immediately apparent, with personal preference playing a key role.

Picture archiving and communications systems (PACSs) are the systems used in hospitals to store, view, and report radiological images. With many vendors available, it is each NHS trust’s decision which to buy into. While PACS implementations will have a common set of functions, different vendors will have subtly different implementations. This leads to trusts choosing a system that is most appropriate to their specific requirements. As such, interoperability, and in particular, image exchange, between trusts becomes an issue.

The use of third-party tools was a clear example of personal preference throughout the interviews. Third-party tools are a department-level decision, and as such, there was considerable variation in the choices made. Participant J said, “we haven’t bought into any of that market [...] because we think at the moment, if you have a one millimeter or less slice contrast-enhanced scan, with our PACS system, you should be able to reconstruct and see sufficiently.” Conversely, participant N had more than 1 third-party tool available to use and described 1 of the third-party tools they use as “fairly ubiquitous in cardiac MRI.”This demonstrates that there is some consistency regarding the tools that are used within specialties, but across specialties, there are differing views toward the built-in tools available in PACS systems.

Throughout the interviews, there was a lot of conversation about 2D versus 3D methods of viewing cross-sectional radiological images, such as CT images. Most participants saw 2D slices as enough. Participant I said, “You scroll through [the 2D slices] using the mouse wheel and I’m building up a picture going through the images. And I have to say that’s more than enough.” Other participants, both radiologists and surgeons, said similar things. 3D techniques were used in specific scenarios, such as looking at the whole surface of a structure, such as the skull, as noted by participant K. Generally, 3D images were used for specific questions, but participants claimed they did not add very much value beyond that.

However, there were situations where 3D techniques were very valuable. Participant H, a thoracic lung surgeon, used a third-party company to reconstruct cross-sectional scans into highly accurate 3D models to be able to plan their operations better. They commended its value, but due to the cost per case, said it cannot be used for every patient; they said, “the frustration is that we can’t have it for every single patient.”It is clear then that traditional 2D techniques are still dominant, but in certain groups, and in certain scenarios, newer 3D techniques are adding value.

XR Maturity for Surgery

It was clear throughout the study that radiologists, surgeons, and other consultants have very different relationships with radiological images. This is unsurprising, but the analysis was an opportunity to delineate these relationships and understand the effect that they have on experiences and requirements of current AR or XR systems.

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It was evident that radiologists spend a much more extended period looking at images as they have a much broader question to answer. Radiologists will answer the clinical question that accompanies the set of images, but they will also look at the rest of the pictured area and report "incidental findings" if required. These incidental findings are a key point of value that the radiologists add. Surgeons, on the other hand, will be looking to answer very specific questions that may affect or change the operation they are about to conduct. One radiologist participant summarized this difference as "If you have a brain surgeon they're going to be an expert in looking at things they can operate on [...] But if you showed them something they can't operate on, like a stroke, they're not going to recognise it. The radiologist adds value in looking at all the other things on the scan." An example of this would be a radiologist measuring a key structure pictured in the scan and including this measurement in their report. The surgeon would then take this measurement as information to use when deciding whether or not to operate or when planning how to approach the procedure.

Across all participants, the experience of AR in clinical practice was little to none, and the opinions of current systems were consistent, particularly among the surgeon participants. The view of the current systems on the market indicated that they added very little value, and definitely not enough to overcome the cost of buying into such technology. Participant E, a cardiac surgeon, referred to the systems they had experienced as "perhaps not quite at the gimmick end of the spectrum, moving a little bit away from that, but still there." There was some inconsistency around opinions as to what role AR could play in the future. Some participants could very much see the potential value in specific areas, while others could not see how AR could improve their current capability or practice in any way. Participant H, an orthopedic surgeon, looked into using a Microsoft HoloLens (Microsoft Corp) to guide the placement of implants, while participant I, a general surgeon, said the presentation of scans as 2D slices is "more than enough"to get the information they need to operate successfully. Participant H acknowledged the potential value of AR for thoracic lung surgery but reinforced the importance of correct registration and how this remains an unsolved issue with the current state of the art.

One of the first things AR was suggested for is IGS, and it is one of the applications that could be most valuable [45]. Most of the surgeons spoken to in this study saw some role for AR to aid surgery as being in the future of their fields. IGS has a very wide scope with many different surgical fields and specific interventions that could benefit from AR, and each will have its own requirements. Robotic surgery is an obvious potential application, as the surgeon is already looking at the operating site through a headset of sorts. Participant J, a robotic thoracic surgeon, when asked about the future said, "there's got to be more things that can be fed into your vision during your operation" and commending the potential of guidance as a way to reduce risk to patients they said, "there have been times, don't get me wrong, where I wonder where I am in the chest, and an overlay at that point would be delightful because your fear factor has gone up." This is a demonstration of where AR could provide tangible value in IGS. It may not be all surgical fields that benefit in this way, though; AR may be introduced in another way. Participant E, a cardiac surgeon, struggled to see how AR could help in their field. Given this constraint, AR may be applied in a different way to add value, such as acting as a head-up display with information like the patient's vital statistics or a view of the preoperative scans floating above the body to act as guidance in a different way.

Increased Reliance on Imaging

Overview

An increased reliance on imaging is a known issue in radiology [8] within the NHS and has multiple contributing factors, but this is likely to have ramifications throughout the organization. Across the interviews, the requirement for efficiency was ever-present, particularly with the radiologists, as were the acceptability factors that new technologies have to work through in the medical field.

Efficiency

Already, there are more scans being taken than can be reported by radiologists, and this is likely to only increase [8] as imaging is an essential part of modern practice [46]. AI for reporting radiological images was brought up regularly in the interviews when talking about the future and efficiency in particular. It was nearly unanimous across all the participants who spoke about it that it would have a big impact on radiology reporting and the number of scans that could be reported in a given time. With an increasing demand being placed on radiologists, the backlog of images to be reported will only grow, increasing waiting times for patients and potentially having negative effects on their care. There was, however, disagreement over exactly how AI would be used. Participant I, a general surgeon, said, "in theory you could replace a radiologist with a computer,"and this was shared among a few others. However, the radiologists saw AI, at least in the foreseeable future, as a tool for radiologists rather than a replacement. Participant K, a neuro-radiologist, said, "having worked in radiology for 6 years and now a year into being a consultant, I think it's difficult to ever imagine a world in which AI could do everything that a radiologist does," and participant N, a thoracic radiologist, said, "AI's got to get pretty good before it's able to do that because that requires a lot of higher functioning and thought [...]-It's a tool, and I see it as a tool going forward."

Similarly to the reporting process, as more imaging is used, MDTs will have to discuss it, and therefore, the process of viewing and manipulating images will have to become more efficient. Radiologists attending an MDT will likely have to review many scans that may have been reported by someone else, quickly, as preparation. Participant N said, "you only get a couple of minutes per case to prep the MDT. Because obviously there's quite a lot of cases, so I couldn't realistically re-report every single scan." It is here that the radiologists check that they agree with how the scan has been reported, particularly in uncertain or complex cases.

Acceptability

When looking to the future of medical technology, there were several factors that repeatedly surfaced through the interviews.

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The first was phrased well by participant N as “technology inertia,”which captures well the resistant nature of the medical field. They went on to say, “I think it’s [the medical field] less open [to new tech], because of the stakes.”This is compounded by other participants saying things such as “people get used to a way of doing things.”This all suggests that even if a new, better technology is available, it takes a significant investment in time and money to implement it in practice. Consultants do not have the time to retrain on new equipment for a very small gain in performance. Current methods are quick through experience and practice and are therefore preferred to retraining. There is a positive attitude toward new and beneficial technology, as evidenced by participant A who said, “I quite like moving with new ideas where possible.”However, this is inconsistent between consultants and not always reflected in the uptake of new technology.

Where there was mention of resistance to new technology, there was often the mention of how age affected this. Participant N said, “to some extent you do rely on younger colleagues coming through to help you innovate, I guess.”This adds to the line of thought that even though new technology may be an improvement, it takes a push to get through the inertia. Just as younger colleagues help the more established to innovate, we must provide a means by which new technology can be effectively demonstrated in order to overcome this inertia.

Discussion

Principal Findings

Across all of the themes described in the results section above, there were several linkages. Efficiency came up explicitly and implicitly throughout the interviews, and this is reflected in the themes. There is a persistent reference toward the fact that there are more images taken than can be reported and that this workload is likely to increase [8]. In this vein, there is generally a positive view that new technology has value to provide the medical field, but a contradictory view that current tools, systems, and processes are good enough to obtain the results required and to do the job well. The opportunity here is to understand the clinical requirements and issues being faced and suggest how AR could be used to alleviate this pressure. This section takes the above results and presents 3 design implications as an output, which stand as the core contribution of this work. These design implications, presented at the end of the following subsections, are intended as considerations to be made when investigating the development of AR systems within health care.

After the interviews had taken place and the analysis had been completed, one of the participants was approached to join as a coauthor (author 4). Here, author 4 reviewed the presentation of the clinical side of the analysis and provided further clinical context to the design implications that are presented below.

Where to Go With the Current Technological Capability

AR has a great deal of value to offer, but it is an emerging technology [47] and has limitations that need to be taken into account when applying the technology. It is important to acknowledge the capabilities of the state-of-the-art AR technology, as well as its limitations. To have this technology deployed in this sector, there must be proof of the value within the limitations. As discussed previously, AR cannot currently reach acceptable margins for IGS. However, over time, as the technology develops, the technological limitations will dissipate, and applications that demand tight margins, such as IGS, will become more feasible. Once AR can be proven to function within the acceptable margins of IGS, there is huge value to be gained [25]. Many of the surgeons interviewed saw the potential value of AR IGS, and the literature supports this [45]. Before this happens, AR still has value to exploit, and it must be determined where the technology can be used to make a difference in its current form. In this section, we suggest radiology as an initial application for integrating AR.

Two key recurring points in our analysis are important here: the desire for efficiency in the workflows around radiological imaging, particularly from radiologists, and the ways in which images are engaged with at each stage of the workflow. Our analysis suggests that there are 2 important points of communication regarding radiological images: the radiologist’s written report and the MDTs. In both the report and the MDTs, the images are, of course, integral, but the time spent on the images after they have been reported can be minimal. This is, in particular, in situations where there is a relatively simple case and the radiologist knows which consultant will be reading the report. They are therefore able to pre-emptively answer the questions the consultant is likely to ask. This matter of minimal time spent looking at images continues to the surgical planning stage. All the surgeons interviewed said that this was a short task where they were looking to answer specific questions that would impact the feasibility of an operation or how an operation would be performed, not a complete reevaluation of the images.

The requirement for efficiency came up repeatedly, particularly from the radiologists’ point of view, and this is consistent in the literature [8]. As discussed previously, the reporting of scans is going to have to become more efficient as the number of scans taken already exceeds the number of scans that can be reported. This extends to the radiologists’ preparation for MDTs, where each case must be reviewed by the radiologist attending the MDT in advance.

In response to these points, we suggest radiology as a starting point for integrating AR into health care, as we believe that the inherent interaction benefits of AR are well placed to be exploited when viewing 3D images. This could give radiologists a better appreciation of the anatomy in a shorter period of time and help them understand relationships between key structures. It may also be used here to take more accurate, quicker measurements of key structures that could help surgeons be better prepared for interventions. This could be of benefit in terms of efficiency.

In addition to this, radiologists spend a significant amount of time with the scans for each case, much more than any other clinician at any other stage in the workflow. This means that the value of using AR can be maximized, and limitations such as the cost of equipment and the learning curve of using it are limited.

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Establishing AR in radiology could then allow some usability, procedural, and technological issues to be researched further as part of this deployment of AR. This could then prepare the technology for future deployment in scenarios where there are currently other limitations. Using this as an opportunity to research AR usability in health care, while adding value to the clinical workflow, would be invaluable, as usability issues are as much of a limiting factor to the implementation of AR as technological issues.

This leads to our first design implication: acknowledging AR technology's limitations and the benefits it can provide, namely the interaction potential, AR should be exploited to help increase the efficiency of radiologists reporting scans. This should be followed by clinical evaluations proving the efficacy of the technology, which may then encourage research into expanding the technology into other disciplines as the technological limitations are mitigated with continued development.

Acknowledging the technology's limitations and working with its advantages will allow value to be added to processes almost immediately. We argue that radiologists are well placed to exploit value from the interactions that existing AR technology affords, likely resulting in increased efficiency; whether that is the whole reporting process or a subset of tasks such as taking measurements.

3D Views Complement 2D Views

Throughout the interviews, 2D versus 3D viewing methods of cross-sectional scans, such as CT and MRI, were a key discussion point. The overwhelming majority were of the opinion that 2D slices of scans in 3 planes were more than enough to gain the information that they required. Some went on further to say that 3D methods lose something over 2D because it is more difficult to look at the internal structures. This was contested in a minority of situations where 3D methods had various specific application areas, such as looking at the surface of the skull and reconstructing lung scans for planning resections. The general consensus was that 3D reconstructions are useful for very specific tasks but add little beyond that.

This suggests, and is intuitive, that the main issue with 3D methods for the participants is the inability to see the same internal structure information that is shown with traditional 2D slices. There was no direct issue with 3D forms; rather, the current 3D viewing methods do not add any value. The opportunity here is to use AR to provide the same information that traditional 2D slices provide while adding value with the third axis. This may enable the radiologist to appreciate the information of the internal structures in the context of the full 3D form in a more intuitive manner. This could also enhance communication and allow a greater shared understanding.

There are examples of using AR in such ways [48], but this interaction has yet to be proven. In order to be accepted by radiologists, the scans shown in 3D in AR must show at least as much information as 2D slices while providing additional value in some other way, such as an enhanced interaction. This value is likely to be in the interaction, as viewing 3D anatomy in 2D images is less intuitive than viewing it in 3D, where further context and relationships may be more visible. The point here is to demonstrate the additional value that AR can provide. This may be difficult, as our analysis suggested that the medical field is quite resistant to change and new technologies. But if it can be demonstrated well and the value translates into better appreciation of structures, quicker turnaround time, or higher throughput, AR will likely become commonplace in radiology offices.

There is clearly big potential in AR IGS, our analysis and the literature [25] show this, but both also show that it is one of the most challenging areas of research. As discussed previously, there are multiple technological issues and usability issues that need to be resolved to unlock this value that are well documented in the literature, with some suggesting that usability considerations of AR are among the most significant potential barriers to the technology's success [19]. A creative, out-of-the-box approach to these usability problems could allow the successful implementation of AR in health care and, therefore, be a source of great value, allowing the benefits that the technology affords to be exploited in a much wider number of scenarios.

Here we argue for the creative implementation of AR, playing to the strengths of the technology and not simply recreating existing capability in a new medium.

As with the example above, using 3D viewing methods has limited use in current practice, and 2D views are dominant. But given the third axis and immersiveness that AR provides, do 3D views provide something that is difficult in 2 dimensions? For example, better appreciation of complex relationships between structures. Or are 3D images easier to interact with, providing an easier or more accurate way to take measurements of structures of interest?

Designers must be explicit about why AR is appropriate for the application and what value it provides while using creative practices in order to realize the full potential of AR. This is the second design implication we suggest: creativity must be used in the implementation of AR; simply recreating existing capability in a new medium should be avoided, and the strengths of AR should be played to in order to add value to the clinical scenario while maintaining prior ability. In the context of 2D versus 3D images, this could mean that the information provided with 2D slices is still available, while also providing additional contextual information with the third dimension.

What Does an "Augmented-Reality-First" World Look Like?

Our analysis suggests that there would be limited value in applying current AR technology individually to surgical planning or for use in MDTs, as current imaging techniques give consultants adequate information to make the decisions necessary in these situations. Furthermore, the images themselves are not used for a very long period for these tasks, and as such, the value gained from viewing the images in AR would have to be great in order to be worth the cost of the equipment and the time taken to put on, boot up, and engage with an AR headset. This is in addition to the initial strain of rewriting procedures around the new technology and the learning curve of engaging with the new medium.

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This can be held true for today's "desktop-first" world, where keyboard and mouse are universally dominant. But looking down the road as AR technology develops and its presence increases in daily life, this is likely to change. In this scenario, where an AR headset could be an extension to a desktop environment, the previous limitations (of cost, learning curve, and clinical practice adjustment) are negated, and the cost-benefit ratio of AR in these situations becomes more amenable.

In this "AR-first" world, the use of an AR headset is as embedded in practice as the use of a normal monitor. There is likely to be a set of tasks that clinicians complete that could be improved in some way with AR. Reporting scans, MDTs, and surgical planning could be 3 examples. For these tasks, the headsets would be ready to run alongside, or instead of, the main desktop environment, and as such, the setup and engagement obstacles are averted. AR would be seamlessly integrated into practices, enabling the benefits to be exploited and made the most of. It is this concept of integration that came up repeatedly in different forms throughout the analysis, for example, learning curve, rewriting processes, resistance to new technologies, and efficiency.

Thinking about speculative scenarios such as this, where certain obstacles are put to one side, allows us to highlight other potentially more nuanced concerns and opportunities that should be considered when designing AR applications for this space. It also allows speculative consideration of the breadth of value the technology could bring in isolation, without being overshadowed by current technological or procedural limitations.

The integration of any new technology into clinical practice can be as significant a hurdle as developing the technology itself, with many concerns residing under the umbrella of "integration"; things such as cost, learning curve, and the rewriting of procedures. However, for the AR, what could be gained if the technology is successfully integrated in the right places? Our analysis suggests that AR brings value in its versatility. It will never be at its best if only used for 1 task. The highest value will be attained when many AR-enhanced tasks are considered. If an AR headset were integrated into practice and ready to deploy for several smaller tasks (such as reporting scans, discussing images in MDTs, and viewing images for surgical planning), much more value would likely be gained relative to implementing just one of those examples.

The first hurdle of successfully integrating AR into 1 point in a workflow and proving value for this one task will likely result in the technology cascading into surrounding tasks, slowly reaching toward maximizing the cost-benefit ratio.

Our analysis suggests 2 main factors would have to be proven to enable an "AR-first" environment. First, is the cost-benefit ratio of the technology. It must be demonstrated that the number of tasks AR could be used for and the benefit that it provides in each of them is worth the cost of buying into the technology. Second, the technology must be integrated into practices well enough to the point where putting on and starting up the headset is not an obstruction to the work being done. This will be a significant challenge as it requires the rewriting of some practices and, therefore, a learning curve when using the systems for the first time. It also requires more targeted human-centered HCI research as opposed to a sole focus on the development of AR technology. Targeted HCI research could map this space more effectively, solving some usability issues and laying the groundwork for more advanced AR technology to stand on.

This leads to the final design implication: AR brings value through its versatility. To obtain the most out of this versatility, it must be considered how AR tools integrate with existing workflows and how they will be used in order to create a seamless transition toward wider uptake of the technology. The technology should be integrated in such a way that negative disruption to existing workflows is avoided and maximum value can be gained from multiple workflows.

Future Work

These design implications aim to help direct and inform future research, while also aiding in decision-making when developing AR applications in this space. Future work will develop these design implications further and test their feasibility by developing a case study application. This case study will conduct further user research and then incorporate the outcomes of this with these design considerations into a prototype. This prototype will then be evaluated by users against the design implications.

This work could also be expanded by focusing on medical education and training. We chose to focus on the clinical radiological applications of AR for this study to contain the scope and focus the design implications. However, participants mentioned educational and training applications, and there is literature supporting their development. Future work could be done to expand or develop these design implications in this space.

Limitations

Our qualitative analysis aims to provide a representative insight into the views and opinions of hospital-based consultants in the United Kingdom along with their views on AR and the role it could play in radiological imaging. However, we must acknowledge the limitations of both the methodology and the dataset.

Our participants were hospital-based consultants, largely from the North East of England, with a few from the North West and South. We successfully recruited a range of participants with a range of specialisms to provide a variety of views and differing contexts, which adds strength and breadth to this work. However, a potential shortcoming of this participant pool was our ability to only recruit men. Where possible, we took appropriate steps to try and recruit women, but in part due to this being a very male-dominated field [49], we were unable to. This will restrict the gender diversity of the perspectives presented, but it reflects the wider demographic trend in some specialties. Future work should aim for a more diverse participant pool.

Our study was limited to the United Kingdom, which we acknowledge may limit the generalizability to wider audiences. However, this limitation is commensurate with the scope of this work.

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We also focused heavily on AR for radiological imaging with little mention of AR for education or training. That is not to say that AR should not be applied to these areas, and it was brought up by participants in multiple interviews. However, for this study, we chose to focus on AR for radiological imaging in order to focus on the design implications.

Conclusions

In this paper, we have presented the results of a thematic analysis of interviews with hospital-based consultants in order to investigate the role AR could play in radiological imaging. We contribute 3 design implications for AR systems within radiological imaging workflows based on the results of our qualitative analysis and frame them in the context of the HCI and medical fields.

The first design implication outlines the desire for efficiency. AR has the potential to provide enhanced interactions, which could allow for a better appreciation of the anatomy and quicker measurements. Radiologists are well placed to exploit this value as a tool to improve efficiency because being able to view and interpret images quickly would allow them to have a higher throughput. Second, we suggest that AR tools need to be built in such a way that no capability available with existing 2D desktop workflows is lost either by using AR to complement existing 2D workflows or by integrating the 2D capability into AR. Finally, AR tools need to integrate and be interoperable with existing radiology systems to minimize disruption to existing workflows, for example, ensuring compatibility with PACS. The value of AR could be exploited across health care organizations if the technology is integrated well, and we speculate on the impact of what an “AR-first” world may look like and how clinical practices may change were this to happen.

This work also adds to the body of literature acknowledging active surgeons’ opinions toward the potential value of AR IGS and motivates areas of future research into AR’s place around radiological images.

Conflicts of Interest

None declared.

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Abbreviations

AR: augmented reality
CT: computed tomography
HCI: Human-Computer Interaction
HMD: head-mounted display
IGS: image-guided surgery
MDT: multidisciplinary team
MRI: magnetic resonance imaging
NHS: National Health Service
PACS: picture archiving and communications system
XR: extended reality

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Feasibility, Subjective Effectiveness, and Acceptance of Short Virtual Reality Relaxation Breaks for Immediate Perceived Stress Reduction in Emergency Physicians: Single-Arm Pre-Post Intervention Study

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Abstract

Background: Emergency physicians face significant stress in their daily work, adversely affecting patient care and contributing to physician burnout.

Objective: This pilot study explored the feasibility, immediate effects, and acceptance of virtual reality (VR) relaxation on perceived stress reduction among emergency physicians.

Methods: The study was conducted at the Department of Emergency Medicine, Bern, Switzerland, in February 2023. All junior and senior physicians were eligible, excluding those with epilepsy, claustrophobia, or severe nausea. Voluntary participants underwent a 6- to 8-minute VR meditation program at their workplace. Subjective short-term stress reduction was measured using a numeric rating scale (NRS) ranging from 0 (“not at all stressed”) to 10 (“extremely stressed”). Feasibility, user acceptance, and technical aspects were evaluated using validated and self-constructed questionnaires.

Results: In total, 35 emergency physicians (median [IQR] age, 32 [30-34] years, 60% female) completed 39 VR simulation sessions. Baseline stress levels (median NRS 4, IQR 2 - 6.5) were significantly reduced post-intervention (median NRS 2, IQR 1 - 4; $P<.001$), particularly among participants with high baseline stress levels. Reported side effects (simulator sickness) were minimal; the median score of presence and immersion according to the questionnaire developed by Slater-Usoh-Steed was 4 (IQR 3 - 4) (scale 1 - 7, with 7=full immersion). User satisfaction was high. Implementation challenges mainly included technical issues and time constraints due to high workload.

Conclusions: This pilot study suggests that brief, relaxing VR sessions may help reduce short-term perceived stress levels in emergency physicians with minimal side effects and high user satisfaction. Future studies should address implementation challenges to optimize integration with clinical workflows.

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KEYWORDS

virtual reality; relaxation; stress; emergency medicine; workplace; burnout

Introduction

Emergency medicine is an inherently high-stress medical specialty due to the urgent and often severe nature of cases, which demand rapid decision-making with potentially life-altering consequences. The additional burden of shift work and disrupted circadian rhythms further exacerbates stress levels among emergency physicians. These factors contribute to a heightened risk of burnout [1-3], posttraumatic stress disorder [4], substance abuse [5], and even suicide [6]. Burnout is a syndrome conceptualized as resulting from chronic workplace stress that has not been successfully managed. It is characterized by feelings of energy depletion or exhaustion; increased mental distance from one’s job, or feelings of negativism or cynicism related to one’s job; and reduced professional efficacy. A recent Swiss investigation confirmed emergency physicians as a medical specialty at great risk for burnout. Over half of the more than 600 respondents met at least 1 criterion for burnout and reported symptoms of mild to severe depression. Alarmingly, 10% of respondents even reported having considered suicide at some point [7]. The implications of burnout extend beyond individual well-being, jeopardizing patient care quality and

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safety and contributing to physicians leaving the profession [7,8]. Therefore, prioritizing personal stress management strategies and advancing research into effective stress reduction methods are essential to maintaining both the quality and sustainability of emergency medicine. This aligns with the World Health Organization's call for addressing health care worker well-being to ensure the resilience of health care systems [9].

Various stress management interventions, such as yoga, mindfulness training, deep breathing exercises, and psychoeducational stress management workshops, have demonstrated effectiveness and are increasingly being implemented in workplace settings. However, the integration of these interventions into fast-paced work environments, such as emergency medicine, remains a significant challenge [10,11].

Virtual reality (VR) is a computer-generated simulation allowing the user to fully immerse himself in an interactive, 3-dimensional environment, typically through a specialized VR headset, or head-mounted device. By blocking out the real world and replacing it with a digital space, VR allows users to engage with virtual objects and environments in real time. This immersion fosters a sense of presence, where users psychologically perceive the virtual world as real, enhancing emotional and cognitive engagement. In relaxation-focused VR applications, this heightened presence allows users to fully disconnect from external stressors, creating a safe space for restorative mental states and stress relief [12].

In the medical field, VR has long been used as a virtual therapeutic tool for managing acute and chronic pain and reducing anxiety across various settings, including the emergency department (ED) [13,14]. Additional applications include treatment for mental health conditions such as cognitive impairment, depression, phobias, and posttraumatic stress [15-17]. Research indicates that VR is an effective therapeutic tool for relaxation, modulating individual stress levels, and potential impacts on the immune response [18]. It offers a cost-effective and accessible option for therapeutic intervention [10,19-21]. Unlike traditional mindfulness practices such as meditation or yoga, VR requires little to no prior experience before positive effects can be achieved [22]. Possible explanations include the attention restoration theory, which posits that exposure to natural environments can replenish cognitive resources depleted by stress. VR can simulate calming natural scenes, providing restorative experiences that reduce mental fatigue and stress [23]. The biopsychosocial model suggests that stress is influenced by biological, psychological, and social factors. VR interventions can address these components by offering immersive experiences that promote relaxation, thereby positively affecting physiological and psychological states.

Potential barriers to the widespread adoption of VR include initial implementation and ongoing maintenance costs, limited accessibility related to hardware availability or user familiarity, uncertainty regarding the duration of beneficial effects, and the risk of adverse reactions such as visually induced motion sickness. Emerging evidence on the use of VR for health care workers suggests promising outcomes. A recent randomized controlled trial involving 32 health care workers demonstrated that VR-based guided meditations are a feasible and accessible mindfulness intervention, potentially even more effective than non-immersive methods [24]. Similarly, brief, tranquil VR experiences have been shown to significantly reduce subjective stress among frontline health care workers during the COVID-19 pandemic [25,26] and to enhance happiness and relaxation among trauma care clinicians [27].

The evidence regarding the use and effectiveness of VR as a stress reduction tool for emergency physicians remains limited. Additionally, implementing VR within the unpredictable and fast-paced environment of an ED presents significant challenges. The feasibility of its application and the acceptance by the emergency team are unclear. Therefore, we conducted a within-subject, repeated measure interventional feasibility pilot study to evaluate the feasibility of deployment of a short relaxing VR simulation in the busy setting of the ED as a stress-reduction tool for emergency physicians; the immediate effect of VR use on self-perceived stress; and the tacceptance of the VR simulation in the study population (user satisfaction, simulator sickness, and sense of presence and immersion).

Methods

Design and Setting

This prospective non-randomized pre-post interventional feasibility pilot study was conducted at the ED of the University Hospital of Bern, Switzerland. As one of the largest EDs in Switzerland, it serves approximately 55,000 patients annually and is staffed by a team of around 70 physicians [28]. The study was carried out between February 1 and February 28, 2023, during daytime hours, contingent on the availability of the study investigators (SH and SS).

The study was conducted on a convenient sample of emergency physicians. Written informed consent was obtained from all participants, including data anonymization and authorization for use in study analysis and publication.

Ethical Considerations

The local ethics committee (Kantonale Ethikkommission Bern, KEK; BASEC number Req-2023‐00018) classified this study as a quality evaluation project, exempting it from the requirements of the Swiss Human Research Act.

Inclusion and Exclusion Criteria

All junior and senior physicians working in the ED of the University Hospital in Bern were eligible for participation. Exclusion criteria included facial or neck injuries, severe nausea or vomiting, claustrophobia, epilepsy, or any other conditions associated with hypersensitivity to light or motion.

Baseline Data

Baseline data included sociodemographic factors (gender, age), the use of visual aids, and smoking habits. Information regarding work routines was also collected, such as the participant's role in the ED, years of professional experience, board certification, workload percentage, frequency of night shifts per month, average break duration, and typical break activities.

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Additionally, participants were asked about prior experience with gaming, VR, and mindfulness exercises ("I regularly use gaming, VR or mindfulness training"). The baseline questionnaire was completed before the initial use of the VR intervention.

Intervention

Physicians were informed about the project in advance during staff meetings, and throughout the study period, reminders were provided through announcements during briefings and informational posters. Additionally, participants were recruited through direct contact by the study coordinators (SH and SS). For half of the 28 days, the study was conducted from 7 AM to 3 PM, and for the other 14 days, from 3 PM to 11 PM, corresponding to the 2 largest daily shifts. During their time at the University Hospital of Bern, the study coordinators were easily reachable via a pager system, allowing physicians to choose an appropriate time for the intervention at their discretion.

The study investigators (SH and SS) informed the participant about the study aims, handed out the information form, ensured the absence of contraindications, responded to the participant's questions, and collected their free, informed, and expressed consent.

The intervention consisted of the application of a 6- to 8-minute VR relaxation program called "Daily Focus," including breathing exercises and a short focus exercise in an imaginary environment. The immersive experience consists of a contemplative, relaxing, futuristic imaginary landscape accompanied by a sound universe specifically composed to relax the user. The scenery and theme changed daily. The content also had interactive capabilities as well, so that the user could take action to affect the VR environment. The user could choose to interact with the environment by fixating one's gaze on an interactive object in the worldscape. "Daily Focus" is part of the commercially available software "TRIPP" developed by TRIPP Inc. (TRIPP Inc.). The company was not involved in any aspects of the study. A commercially available stand-alone head-mounted display (Meta Quest 2; Meta) was used. When it became apparent that background noise at the University Hospital of Bern's workplaces impaired the sense of immersion for some participants, noise-cancelling headphones (JBL Live 650BTNC; JBL) were introduced to reduce ambient sounds. As the physicians' experience with VR head-mounted displays was limited, the users were supported by the study team in the technical application when needed (SH and SS). In case of a medical emergency requiring the immediate presence of the physician, the VR simulation was interrupted. The briefing, completion of the consent form and questionnaires, and the intervention itself took approximately 15 minutes in total. The duration of the evaluation and intervention was intentionally kept as short as possible to minimize barriers to participation.

Outcomes

Feasibility

Feasibility was assessed using technical details of the simulation (location of the simulation, ie, directy at the workplace vs quieter location, interruptions of the simulation and reasons for interruptions, and timing of the intervention), as well as with free text comments of the users and feedback collected from the study team (SH and SS).

Immediate Effect of VR Use on Perceived Stress

Perceived stress reduction was measured as the difference between the self-reported stress level directly before and after the intervention on a numeric rating scale (NRS-11) scale from 0 to 10 (0="not at all stressed" to 10="extremely stressed"). This simple measure was selected due to its strong correlation with the well-validated Perceived Stress Scale 14 (PSS-14) [29]. Furthermore, a threshold value of 6.8 on the self-reported scale has been shown to effectively predict high stress levels, corresponding to a PSS-14 cutoff score of ≥7.2, and was therefore chosen to identify individuals experiencing high stress, similar to Beverly et al [25,29].

User Acceptance

User acceptance was evaluated using the following questionnaires:

Visually induced motion sickness was assessed according to the Simulator Sickness Questionnaire (SSQ) from Kennedy et al [30].

Presence and immersion in the virtual world were determined according to the 6-item questionnaire developed by Slater-Usoh-Steed (total score ranges from 1=no immersion to 7=full immersion) [31].

User satisfaction was assessed using a self-constructed 8-item questionnaire (1: I enjoyed the simulation experience; 2: The headset and headphones felt comfortable; 3: The audio quality was clear and enjoyable; 4: The image quality was visually pleasing; 5: The simulation helped to reduce my stress level; 6: I would use this simulation again for relaxation; 7: I would recommend this simulation to others; 8: The simulation can be conveniently performed directly at the workplace). Responses were collected on a 5-point Likert scale (1="totally disagree" to 5="totally agree") immediately following the intervention.

Furthermore, a self-constructed 6-item user acceptance questionnaire was sent out 2 weeks after the final intervention via email to all physicians working in the department, with a particular focus on understanding the limiting factors that prevented users from taking a break with VR (1: I couldn't find time during my shift because the workload was too high; 2: I felt it wasn't worth investing the time because I preferred to finish my documentation as early as possible to end my shift on time; 3: I didn't enjoy the simulation (virtual environment/voice guidance), but I could imagine using it more often with a different program; 4: I experienced side effects that overshadowed the positive aspects of the VR breaks; 5: I prefer to spend my breaks differently; 6: I didn't think about it/forgot that the option was available. Responses were collected on a 5-point Likert scale (1="totally disagree" to 5="totally agree").

Statistical Analysis

Statistical analysis was carried out using Python (version 3.9.12) and the following packages: NumPy, SciPy (matplotlib, seaborn). Baseline characteristics are presented as numbers and

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percentage or median and interquartile range (IQR) using descriptive statistics as appropriate. Pre- and post-simulation comparisons (stress level) were performed with the Wilcoxon signed-rank test.

We performed subgroup analyses, including participants with high stress levels defined as NRS-11 ≥6.8 (similar to Beverly et al [25]) with the Wilcoxon rank sum test.

Comparisons between independent groups (eg, male vs female, status of active patient care involvement, prior experience with mindfulness training, gaming experience) were carried out by Wilcoxon rank sum or Kruskal-Wallis test depending on the variable.

A $P<.05$ was considered significant.

Effect sizes with 95% CI for stress levels before and after the simulation were determined by Cohen *d*. Effect size was determined as follows: Cohen $d<0.5$ small, 0.5 - 0.8 moderate, and >0.8 large.

Results

Baseline Characteristics

Out of 67 physicians (61% female), 35 working in the ED completed the study (response rate 52.2%). The average age of the participants was 32 (IQR, 30 - 34) years, with 60% (n=21) being female. Further demographic characteristics as well as break behavior are reported in Table 1.

Participants were asked to rate their experience with gaming, VR, and mindfulness training ("I regularly use gaming, VR or mindfulness training") on a scale from 1 ("Strongly disagree") to 5 ("Strongly agree"). For gaming, the median score was 1 (IQR 1 - 2), no participants had prior experience with VR, and for mindfulness training, the median score was 2 (IQR 1 - 3).

Table . Baseline characteristics including break routine (N=35).

Item	Value
Gender, n (%)	
Male	14 (40)
Female	21 (60)
Age in years, median (IQR)	32 (30-34)
Use of visual aids, n (%)	16 (45.7)
Smoker, n (%)	0 (0)
Professional role, n (%)	
Resident physician	27 (77.1)
Fellow physician	2 (5.7)
Senior physician	6 (17.1)
Board certification, n (%)	12 (34.3)
Work experience, years, median (IQR)	5 (4-7)
Employment level, %, median (IQR)	80 (80-100)
Frequency of night shifts per month, median (IQR)	4 (3-5)
Break routine, n (%)	
No breaks	6 (17.1)
Break at the workplace with constant availability	29 (82.9)
Break at the workplace without constant availability	0 (0)
Average break time in minutes, median (IQR)	15 (10–20)

Feasibility and Technical Details of the Interventions

Out of 35 participants, 4 (11.4%) individuals completed the intervention twice, resulting in a total of 39 interventions. The majority of interventions (n=23, 59%) occurred directly at the workplace, while 41% (n=16) took place in designated rooms away from the workplace. Out of 39 interventions, 6 (15.4%) experienced interruptions. The majority of these (66.7%, n=4; 10.3% of all interventions) were due to technical issues, while the remaining 2 (33.3%, 5.1% of all interventions) were caused by urgent medical duties requiring participant attention.

In terms of shift schedules, 61.5% (n=24) of interventions were conducted during the morning shift (7–3 PM), 35.9% (n=14) during the afternoon shift (3 PM–11 PM), and 2.6% (n=1) at the end of a night shift (7 AM). During most of the interventions (n=27, 69.2%), participants remained actively engaged in patient care, whereas about one-third (n=12, 30.8%) were conducted after shift hand-over, with the participants no longer directly

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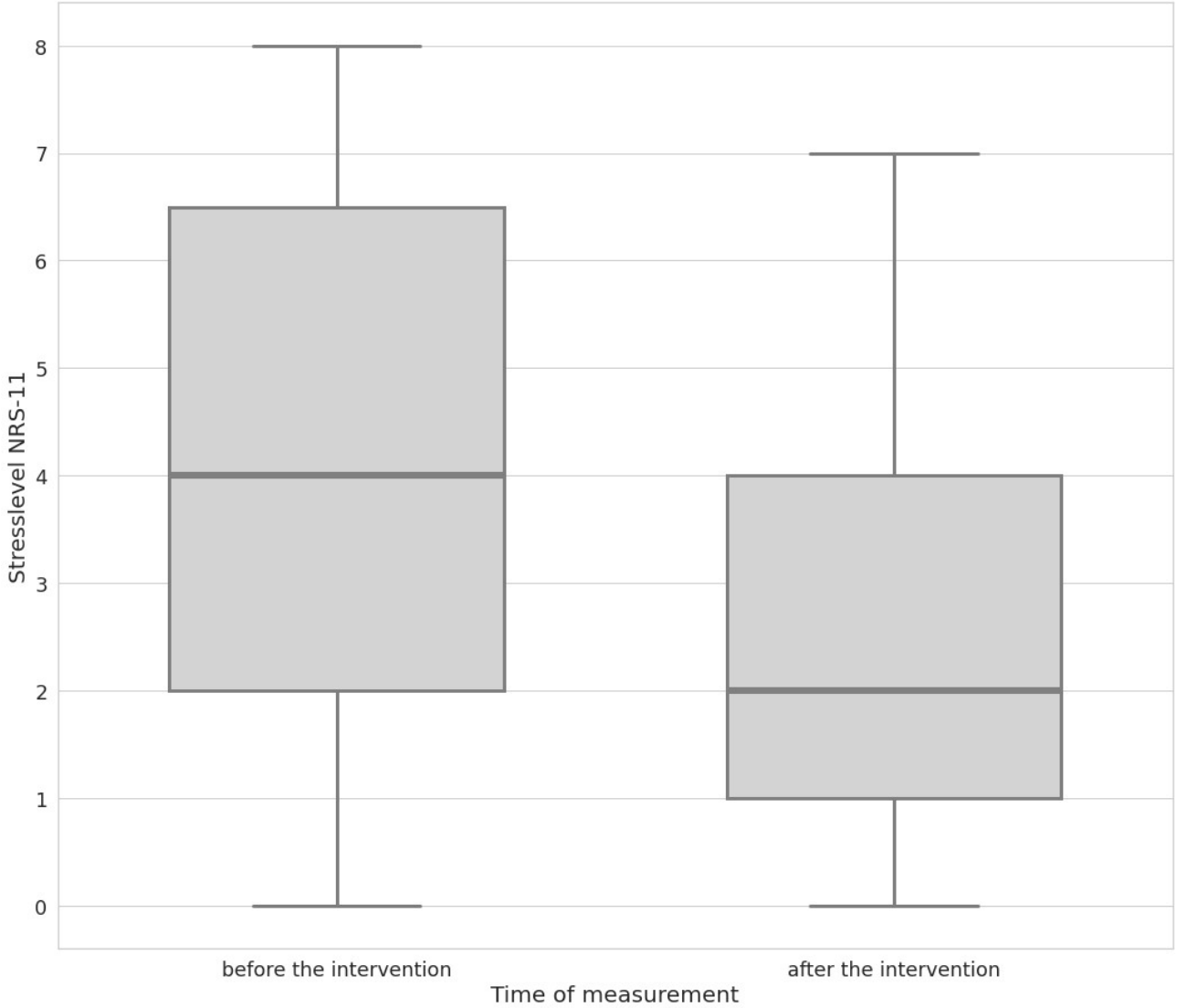
responsible for patient care but remaining engaged in administrative tasks.

The free-text comments were predominantly positive, highlighting the usefulness and effectiveness of the intervention. However, some criticisms were noted regarding the comfort of the headset and aspects of the simulation itself. Suggestions included a more photorealistic scenario and reduced voice guidance during the simulation. Feedback indicating that ambient emergency noises disrupted immersion was addressed by introducing the use of headphones and conducting sessions in quiet, isolated rooms whenever possible. Additionally, participants frequently mentioned that during active patient care, they were often unable to fully engage with the simulation or felt unable to allocate sufficient time for the intervention.

Immediate Effect of VR Use on Perceived Stress Reduction

The baseline median stress level was 4/10 (IQR 2 - 6.5), which was reduced to 2/10 (IQR 1 - 4) after the intervention (P<.001) (Figure 1). The effect size was calculated as Cohen d=1.28 (95% CI 0.84 - 1.72), representing a large effect.

Figure 1. Immediate effect of virtual reality use on perceived stress reduction. Comparison of stress levels before and after the intervention. NRS: numeric rating scale.



In total, 10 participants reported high baseline stress levels (≥6.8). In this group, the intervention was even more effective, reducing the stress level from 7/10 to 4.5/10 (P<.001) (Figure 2). Only one individual reported a high stress level after the intervention. In this case, the simulation was terminated after 2 minutes due to an audio malfunction.

No significant differences in stress reduction concerning the variables gender (P=.767), prior experience with mindfulness training (P=.376), gaming experience (P=.489), or involvement in active patient care (P=.912) were found.

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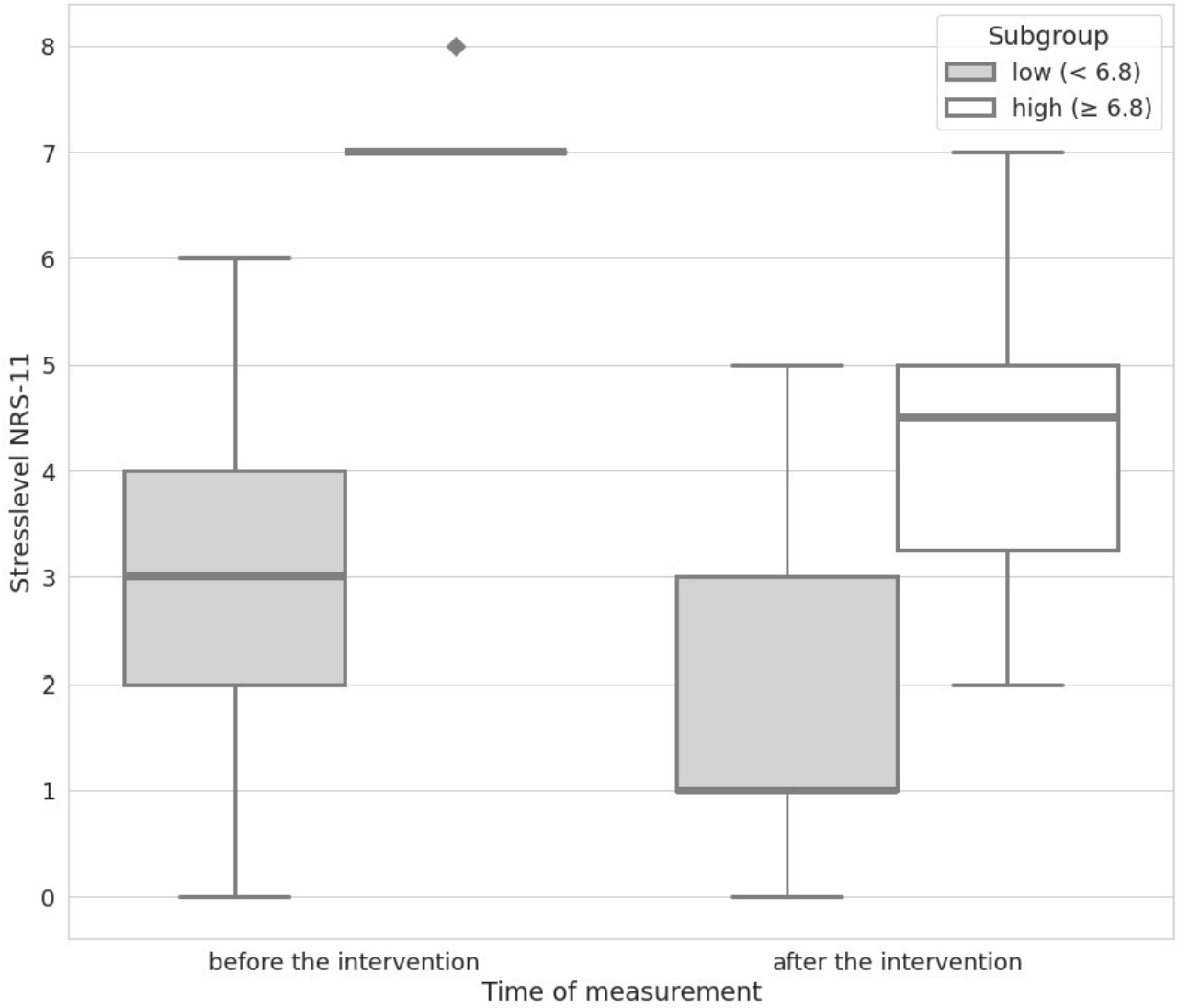
Figure 2. Immediate effect of virtual reality use on perceived stress reduction according to stress level. Comparison of stress levels of subgroups with low and high stress before and after the intervention. Outliers (values ≥1.5×IQR) are indicated as diamonds. NRS: numeric rating scale.



User Acceptance of the VR Simulation

Visually Induced Motion Sickness

The median of the total score according to the SSQ from Kennedy was 80 (IQR 0 - 161) (range 0 - 813).

Presence and Immersion

The median score of presence and immersion according to the questionnaire developed by Slater-Usoh-Steed was 4 (IQR 3 - 4) (with 7=full immersion).

User Satisfaction

Results of the user satisfaction survey are detailed in Figure 3.

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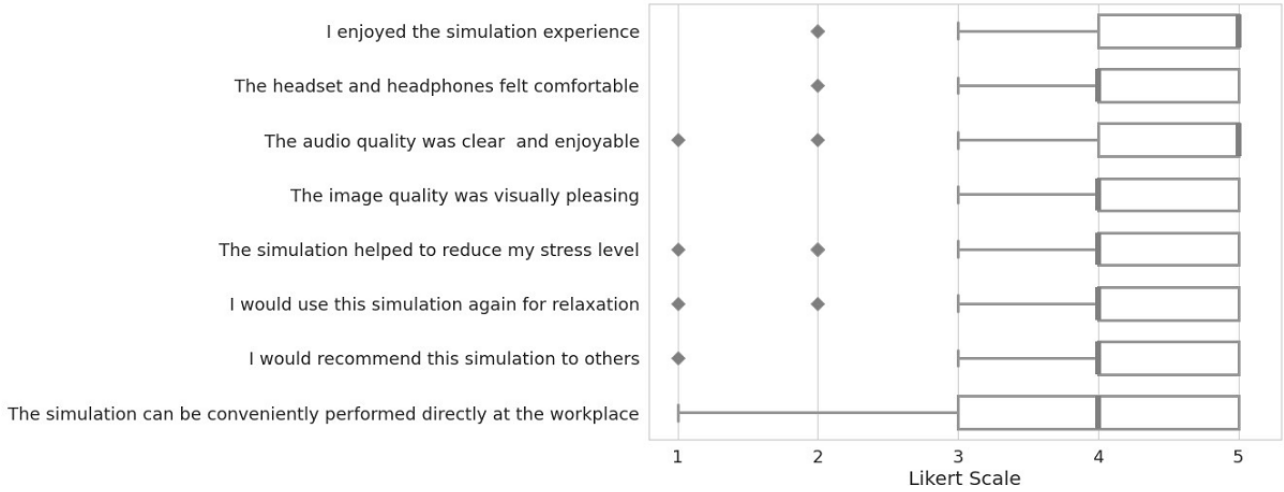
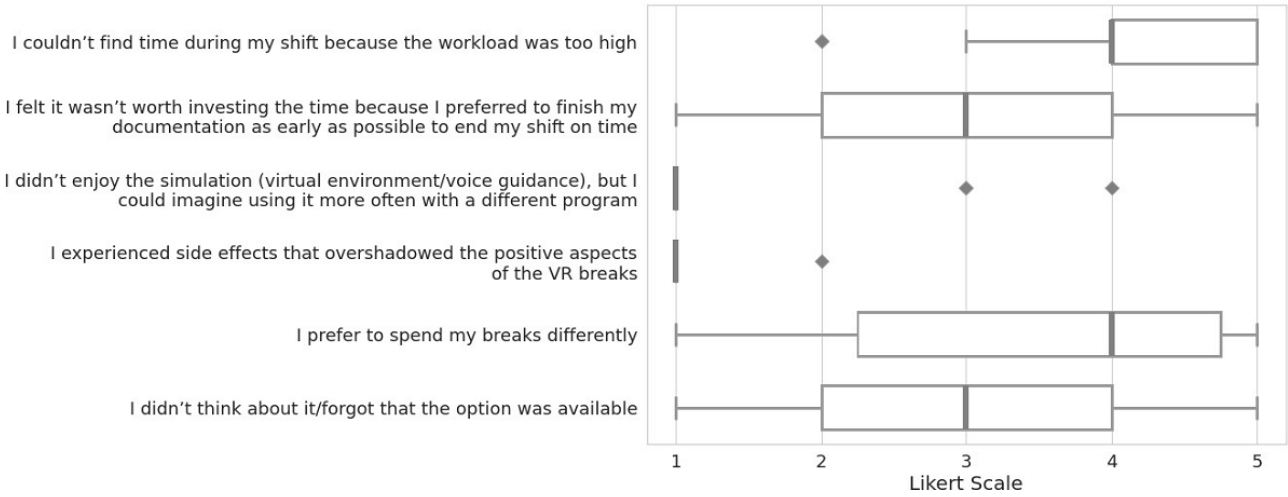
Figure 3. User satisfaction survey. Results of the user satisfaction survey. Answers on a 5-point Likert scale from 1="totally disagree" to 5="totally agree" directly after the intervention. Outliers (values ≥ 1.5×IQR) are indicated as diamonds.



Acceptance Survey

In total, 16 physicians completed the 6-item retrospective acceptance survey sent out 2 weeks after the intervention period (response rate 24%). Answers are depicted in Figure 4.

Figure 4. Retrospective acceptance survey. Results of the retrospective acceptance survey. Answers on a 5-point Likert scale from 1="totally disagree" to 5="totally agree." Outliers (values≥1.5×IQR) are indicated as diamonds.



Discussion

Overview

This pilot study evaluated the feasibility, immediate effect of VR use on perceived stress reduction, and acceptance of VR simulation as a short break intervention within the high-pressure environment of an ED.

We observed a significant reduction in self-reported stress levels, decreasing from 4/10 to 2/10, with a large effect size. Importantly, 26% of participants reported high stress levels prior to the intervention, in which the stress-reducing effect of VR was particularly pronounced. No significant differences in stress reduction were observed across demographic or experiential variables, including gender, prior mindfulness training, gaming experience, or engagement in active patient care during the intervention.

Acceptance was high with minimal side effects. Despite its effectiveness, challenges were noted in implementing VR breaks, primarily due to the substantial time constraints faced by health care professionals. These logistical barriers may limit the practical application of this intervention in routine clinical practice.

Feasibility

The simulation was carried out with minimal technical issues or interruptions. Notably, a significant number of individuals voluntarily participated in the study, and the overall feedback was highly positive, indicating strong interest and acceptance of the concept.

One limitation observed was the execution of the simulation directly in the busy ED environment at the participants' desktops, which occasionally resulted in distracting background noise that could impact participants' focus. To address this issue, noise-canceling headphones were introduced, and approximately

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40% of the simulations were conducted in quieter settings in the ED.

Stress Reduction

This study demonstrated a significant reduction in subjective stress levels, with an average decrease of 2 points on the NRS-11 scale following a 6- to 8-minute VR simulation. These findings align with previous studies investigating VR-based stress reduction in high-stress medical environments, particularly during the COVID-19 pandemic.

For example, Beverly et al [25] conducted a similar study involving frontline health care workers. They observed comparable reductions in stress (mean change –2.2 on a visual analogue scale from 1 to 10, effect size Cohen d = 1.08) and high levels of acceptance after a 3-minute 360-degree cine-VR simulation featuring a nature scene. Similarly, Putrino et al [32] reported on the effectiveness of "Recharge Rooms," immersive multisensory environments designed to alleviate stress among frontline health care workers during the pandemic. These rooms incorporated visual projections of natural landscapes, calming sounds, and soothing scents. In a study involving 496 participants, average self-reported stress scores decreased significantly from 4.58 to 1.85 on a 6-point scale after a single 15-minute session, with high user satisfaction reported. Further supporting these findings, Nijland et al [26] evaluated the use of 10-minute VR relaxation breaks in 360° immersive environments for 86 ICU nurses during their shifts. This intervention demonstrated similar reductions in stress levels (mean change –1.4 on a visual analogue scale from 1 to 10) and high user acceptance. However, a key barrier identified across studies, consistent with our findings, was the high workload of health care professionals, which limited the feasibility of integrating VR-based interventions into routine clinical practice.

While no studies specifically targeted the ED setting, Adhyaru and Kemp [27] reported on the use of VR relaxation interventions among 39 predominately female physicians working in a fast-paced trauma service. The study highlighted the positive impact of 10-minute VR relaxation sessions using the Nature Treks application, demonstrating the potential for VR-based interventions in similar high-stress environments. Participants engaged in these sessions within a designated well-being room during their workday, immersing themselves in natural environments. Post-intervention, participants reported significant increases in feelings of happiness and relaxation, accompanied by notable decreases in sadness, anger, and anxiety. Objective measures also showed a significant reduction in heart rate, indicating decreased physiological arousal.

Although the short-term effects of various VR applications appear comparable, meaningful comparisons remain challenging due to differences in study settings, target populations, specific content and design of VR software, as well as external factors such as the surrounding environment and circumstances (eg, pandemic conditions). These variations significantly limit the generalizability and interpretability of findings across different VR studies.

Speculatively, VR's effectiveness might be attributed to attention restoration theory, proposing that immersive restorative environments help replenish cognitive resources depleted by stress [23]. Additionally, the biopsychosocial model posits that immersive VR experiences can modulate neurophysiological responses, such as decreasing sympathetic nervous system activation and reducing cortisol levels, thereby alleviating stress [18,21].

Nevertheless, the optimal design of VR-based stress interventions remains unclear. Current literature varies widely regarding realism (naturalistic vs abstract scenarios), activity levels (passive viewing vs interactive tasks), and intervention types (guided meditation vs free exploration). These variations underline the necessity for further research using rigorous experimental designs with both cognitive and neurophysiological methodologies. Future studies should systematically investigate these variables to identify the most effective VR intervention formats and better elucidate the underlying mechanisms driving VR-induced stress reduction.

As this was a pilot study, only short-term (pre-post) effects regarding stress reduction were evaluated. However, findings from several studies provide initial data supporting the effectiveness of long-term VR-based programs for reducing stress, anxiety, and burnout among different health care professionals [24,33-36]. A recent study in the ED explored the effectiveness of a 4-week VR-based mindfulness intervention using brief guided breathing exercises. Participants using VR demonstrated greater improvements in relaxation, as measured by heart rate variability (HRV), compared to a mobile app. Regular VR use led to increased relaxation effectiveness over time, suggesting VR's suitability for long-term mindfulness programs [24]. Several aspects require further study, such as examining patterns in VR mindfulness effectiveness across varying workload conditions and shifts. Additionally, stress and relaxation trends could be assessed by demographic or professional differences like job role or experience. It would also be valuable to explore the cumulative impact of VR sessions on chronic stress and burnout over time, analyze the timing of sessions related to well-being outcomes, and investigate how individual personality traits or baseline stress resilience influence responses to VR interventions.

User Acceptance

With regard to side effects, the intervention proved to be largely free of adverse effects. This aligns with findings from other studies that have used VR as a relaxation tool [14,36,37].

The results indicated only moderate levels of immersion, consistent with findings from another study investigating the use of VR for pain reduction in our ED setting [14]. For both studies, we attribute this moderate immersion to environmental factors such as background noise, interruptions, and the generally high-stress atmosphere. These factors likely relate to the aforementioned limitations in implementing VR interventions within the workplace.

Overall, user satisfaction among participants was very high. Comfort, as well as the audio and visual quality, received considerable praise, particularly after the introduction of noise-canceling headphones. Participants also reported high subjective effectiveness for relaxation, with strong agreement

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on statements such as, “I would use this simulation again for relaxation” and “I would recommend this simulation to others.”

However, the statement “The simulation can be easily conducted in the workplace” received less agreement. This raises the question of whether and how the intervention could be better integrated into the ED workplace setting. As revealed by the retrospective questionnaire, many participants did not engage in the intervention due to work-related time pressures. This highlights a broader issue also reflected in the baseline survey results. On average, physicians reported taking only 15 minutes for breaks during their shifts.

The strong agreement with the statement “I couldn’t find time during my shift because the workload was too high” further underscores a structural challenge related to workload and break culture within the workplace. Spontaneous comments from participants and the low-medium baseline stress levels suggest that participants only took time for the intervention after the peak of their stress had passed. Given that the highest levels of work-related stress for emergency physicians typically occur during the care of critically ill patients, this timing is likely unavoidable—and perhaps even desirable. As highlighted in a recent phenomenographic study on well-being interventions in the ED, the demands of the job simultaneously necessitate and limit the implementation of effective interventions to support staff well-being in this challenging environment [38]. Possible solutions for further interventions include protected break and VR break times or scheduling VR breaks during lower workload periods.

Some participants criticized the fantasy-style design of the simulation, expressing a preference for a more naturalistic environment. However, the software used has been successfully applied in several other settings [21,34,37]. Meanwhile, many studies investigating VR for stress reduction have used realistic nature-based simulations, such as a forest. Such an approach may further enhance relaxation, as numerous studies have demonstrated that exposure to forests and nature in general promotes relaxation [10,18,20].

While we demonstrated technical feasibility and user acceptance of short VR interventions, factors such as device affordability, software licensing costs, and the scalability of deploying VR systems across various clinical settings must be carefully considered.

Limitations

This study has several limitations that should be considered when interpreting the results. First, and mainly, the absence of a control group makes it impossible to definitively attribute the observed stress reduction to the VR intervention itself. Without a comparator, we cannot rule out alternative explanations, such as placebo effects, spontaneous recovery, or other external factors. However, given the feasibility nature of this pilot study and the promising results observed, these findings provide a solid foundation for future controlled trials. These should incorporate a more rigorous design, eg, a randomized controlled trial with a control group or an active control condition (eg, a non-VR relaxation technique, like guided breathing exercises). Second, no other structured assessments for burnout or depressive symptoms were conducted. These psychological dimensions are closely linked to stress and could have provided additional insights into the broader mental health effects of the intervention. Additionally, no physiological stress markers (eg, cortisol levels, HRV, and electrodermal skin activity) or other objective parameters were collected. Sole reliance on self-reported stress levels introduces potential biases (eg, social desirability), which may have affected the accuracy of the findings. However, as we wanted to keep the intervention as short as possible, we abstained from using an extensive test battery or setup. Future studies should include a multimodal stress assessment, potentially integrating real-time biometric data using wearable technology or mixed-reality applications. The single-center design and small sample size may also limit the generalizability of the results, as factors specific to the study setting could have influenced outcomes. Selection bias may also have influenced the results, as participants might have been particularly motivated, tech-savvy, or predisposed to respond positively to VR-based interventions. This self-selection could limit the generalizability of the findings to a broader population. The potential for a novelty effect must also be acknowledged. Participants’ stress reduction could partially stem from the excitement or novelty of using VR technology rather than the intervention’s intrinsic therapeutic effects. Furthermore, this study did not assess long-term effects. The sustainability of stress reduction over time remains unclear, and follow-up assessments would be necessary to determine whether the observed benefits persist beyond the immediate post-intervention period.

Ultimately, while the results are encouraging, future research should focus on a randomized controlled design, incorporate a multimodal assessment of stress, depression, or burnout, including objective biological stress markers, assess long-term effects, and involve larger, more diverse populations to strengthen the evidence base for VR interventions in stress management in the health care setting. Furthermore, it is essential to identify the specific aspects of the experience that elicit the most significant responses. For example, archival data before and after the Covid-19 pandemic show that passive content with less interactivity resulted in a greater positive mood state after the COVID-19 onset, likely related to its capacity to reduce stress, facilitate restoration, and improve persistent affective states in stressful environments [39].

Conclusions

In summary, this pilot study adds to the growing evidence supporting the use of VR for workplace well-being by demonstrating the feasibility and short-term effectiveness of immersive VR simulations for stress reduction among emergency physicians. A brief VR-based relaxation break conducted directly in the ED workplace significantly decreased subjective stress levels, with high user satisfaction and minimal side effects reported. However, implementation challenges were evident, primarily due to the significant time constraints faced by health care professionals in this high-pressure environment. These findings highlight the potential of VR as a tool to enhance workplace well-being while underscoring the need for strategies to overcome logistical barriers and better integrate such interventions into routine clinical practice. Future studies should

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focus on long-term effects, objective stress measures, and scalable implementation strategies to further validate and optimize this approach.

Acknowledgments

We would like to thank the entire team at the Department of Emergency Medicine at the University Hospital Bern, Switzerland, for their openness to this intervention and their willingness to participate in the study. The generative AI tool ChatGPT4.0 by OpenAI was used for language editing.

Data Availability

Data contain potentially identifying or sensitive employee information. Data used in this study are available upon reasonable request from the corresponding author at the Emergency Department of the University Hospital Bern, Switzerland to researchers eligible under Swiss legislation to work with codified research data.

Authors' Contributions

All authors contributed to the design of the project. TB and TCS conceptualized the study. SH and SS collected the data. SH, TB, and TCS analyzed and interpreted the data. TB and SH wrote the manuscript. All authors revised, reviewed and approved the manuscript before submission. TB and SH contributed equally.

Conflicts of Interest

TCS holds the endowed professorship of emergency telemedicine at the University of Bern sponsored by the Touring Club Switzerland. The sponsor has no influence on the research or decision to publish.
All other authors have nothing to disclose.

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Abbreviations

ED: emergency department
IQR: interquartile range
NRS: numeric rating scale
PSS-14 : Perceived Stress Scale 14
SSQ: Simulator Sickness Questionnaire
VR: virtual reality

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At-Home Virtual Reality Intervention for Patients With Chronic Musculoskeletal Pain: Single-Case Experimental Design Study

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Abstract

Background: Virtual reality (VR) could possibly alleviate complaints related to chronic musculoskeletal pain (CMP); however, little is known about how it affects pain-related variables on an individual level and how patients experience this intervention.

Objective: This study aimed to gain detailed insight into the influence of an at-home VR intervention for pain education and management on pain-related variables, and to explore its feasibility and general experience.

Methods: The study applied a single-case experimental design in which an at-home VR intervention was used for 4 weeks by patients with CMP who were on a waiting list for regular pain treatment. Outcome measures included pain-related variables, functioning, and objectively measured outcomes (ie, stress, sleep, and steps). Outcomes were analyzed using data visualization (based on line plots) and statistical methods (ie, Tau-U and reliable change index) on an individual and group level. In addition, a focus group was conducted to assess feasibility and general experience to substantiate findings from the single-case experimental design study. This focus group was analyzed using inductive thematic analysis.

Results: A total of 7 participants (female: n=6, 86%) with a median age of 45 (range 31 - 61) years participated in this study. A dataset with 42 measurement moments was collected with a median of 280 (range 241 - 315) data points per participant. No statistically significant or clinically relevant differences between the intervention and no-intervention phases were found. Results of the visual analysis of the diary data showed that patients responded differently to the intervention. Results of the focus group with 3 participants showed that the VR intervention was perceived as a feasible and valued additional intervention.

Conclusions: Although patients expressed a positive perspective on this VR intervention, it did not seem to influence pain-related outcomes. Individual patients responded differently to the intervention, which implies that this intervention might not be suitable for all patients. Future studies should examine which CMP patients VR is effective for and explore its working mechanisms. In addition, future larger trials should be conducted to complement this study's findings on the effectiveness of this intervention for patients with CMP and whether VR prevents deterioration on the waiting list compared with a control group.

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KEYWORDS

virtual reality; VR; chronic musculoskeletal pain; CMP; single-case experimental design; SCED; user experience; self-management; musculoskeletal pain

Introduction

Chronic musculoskeletal pain (CMP), defined as pain lasting longer than 3 months, is a major problem and prevalent in approximately 20% of adults [1,2]. CMP is associated with a decrease in quality of life and mental health problems [3,4], next to the significant financial and societal burden [1]. Unfortunately, the effectiveness of biomedical treatment options for CMP does not seem to be very promising [5], since CMP usually is a complex problem with an interplay of biological, psychological, and social factors [6].

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Given the complexity of CMP, treatment should use a holistic approach in accordance with the biopsychosocial model [5] and neuromatrix theory [7]. Unfortunately, most more complex, holistic interventions for CMP have a waiting list period, which could have a deteriorating effect on patients with CMP [8]. Therefore, it might be sensible to already start treatment during this waiting list period. Virtual reality (VR) is a novel, therapeutic technology that is suitable for stand-alone, at-home treatment [9]. VR is defined as "a collection of technologies that allow people to interact efficiently with 3D computerized databases in real time using their natural senses and skills" [10].

Even though VR for CMP seems promising, much is still unknown about its underlying mechanisms (eg, distraction or skills-building) [11] and influences on an individual level, as previous studies applied a nomothetic approach [9]. Since the principles underlying VR for CMP remain a black box [12], an idiographic approach is warranted for a complex condition like CMP to gain insight into the influence of VR on individual outcomes [13]. A single-case experimental design (SCED) study could increase understanding of the individual experience [14]. SCED studies apply detailed assessment at numerous timepoints [15] and have benefits over other designs, including patients serving as their own control and being especially suitable for heterogeneous samples, like CMP patients with a variety of conditions [16]. A recent SCED study on VR for chronic low back pain (CLBP) found that VR has the potential to reduce CMP-related complaints, possibly through a combination of distraction and modification of attitudes and beliefs [17]. We expect that this VR intervention is suitable not only for patients with CLBP but also for patients with other CMP conditions. In addition, we hypothesize that VR might influence other outcome measures like pain acceptance and interference, functioning, and objectively measured outcomes.

Therefore, the aim of our study was to (1) explore whether and how a VR intervention has an influence on pain-related variables on an individual level and (2) explore the feasibility and general experience of the VR intervention. To do so, patients with CMP received a pain education and management VR intervention at home while they were on a waiting list to receive pain treatment.

Methods

Design

This mixed methods study consisted of 2 parts. The first part of the study applied a nonconcurrent single-case experimental ABA-design on at-home, VR intervention for patients with primary or secondary CMP who were on a waiting list to receive regular pain treatment. Phases A1 and A2 (no intervention) were 1 week before and 1 week after the VR intervention, fulfilling the criterion for a sufficient baseline in single-case designs [18]. Phase B (VR intervention) lasted a total of 4 weeks. To report and conduct the study, the Single-Case Reporting Guideline in Behavioural Interventions (SCRIBE) was used [19], more details in Multimedia Appendix 1. The second part of this study consisted of 1 focus group with patients with CMP who received the intervention. The aim of this focus group was to gain more insight into the general experience and feasibility (including acceptability and practicality, which includes participants' satisfaction and ability to use a new intervention [20]) of the VR intervention and substantiate findings from the SCED study. This part of the study was reported and conducted according to the Consolidated Criteria for Reporting Qualitative Research (COREQ) reporting guidelines [21], more details in Multimedia Appendix 2. Recruitment and completion of the study procedures was from February 2023 to April 2023.

Ethical Considerations

The medical ethics committee of Radboudumc provided a non-WMO (medical research involving human subjects act) waiver (2022‑15829) to conduct this study. The ethics committee of the University of Twente approved this study (RP 2022‑174), as well as local ethics committees of the participating health care organizations. Participants gave written informed consent before any study procedures and received €50 (US $52) for participation in this study after finishing all procedures. All participant data was pseudonymized.

Participants

Participants were recruited from 4 secondary care organizations in the Netherlands (ie, Roessingh Centrum voor Revalidatie, Roessingh Pijnrevalidatie, ZGT Nocepta, and Deventer hospital). Patients were deemed eligible for participation if they (1) were aged 18 years or older, (2) had primary or secondary CMP, (3) finished first-line treatment, (4) were open to treatment with biopsychosocial elements, and (5) were willing and able to comply with the study protocol. Patients were excluded if they (1) were not capable of finishing the intervention due to physical (eg, face wounds, severe visual impairment), mental (eg, severe sensitivity to stimuli), or practical problems (eg, insufficient tech literacy); and (2) had no comprehension of the Dutch language.

Intervention

In this study, the Conformité Européenne (CE)–certified VR intervention Reducept was used as a daily at-home intervention for 10 to 30 minutes per day for 4 weeks, thereby following the intervention protocol dosage from the intervention provider. Besides pain neuroscience education (PNE), the VR intervention incorporates elements of several psychological therapies into 1 application: hypnotherapy, mindfulness, acceptance and commitment therapy (ACT), and cognitive behavioral therapy (CBT). The intervention was described in more detail in previous studies [9,22,23]. The Pico G2 4K (Bytedance) head-mounted display (HMD) was used in this study to provide the immersive VR intervention.

Procedure

Patients visited one of the participating centers of this study for their pain treatment. After their intake, but before starting their secondary care treatment (either [non]invasive pain treatment or interdisciplinary pain rehabilitation), patients were screened by their health care professional for possible participation in the study. Patients were given the opportunity to participate in our study or wait for their treatment on the waiting list without receiving any other treatment. In addition, participants were made clear that participating in this study would not have any influence on the pain treatment they were on a waiting list for. If a patient was deemed eligible, he or she was contacted by

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their health care professional, who gave a brief explanation about the study and asked for permission to forward the patient's contact details to the researcher (through a fully secured app: Siilo). Next, the researcher contacted the patient by phone and gave more detailed information about the study and asked the patient to contemplate participating in the study. The patient enrolled in the study by signing the informed consent and received the first questionnaires (T0), the Garmin Forerunner 255 wearable, and the VR headset. The wearable and VR headset were provided by the researcher and used by participants for the duration of the study procedures. In the first week, a detailed baseline was obtained by asking patients to use the wearable and fill in the diary and weekly questionnaires, without receiving the intervention (phase A1). After this phase, participants carried out the intervention at home for four weeks (phase B). Next, patients waited a week (phase A2) before receiving the pain treatment he or she was on the waiting list for. After phase A2 and during the period patients received the pain treatment they were on a waiting list for, patients returned the used equipment (ie, VR headset and wearable) and were invited to the online focus group, using Microsoft Teams, about the feasibility and general experience of the intervention. The focus group was conducted by 2 researchers (SS and LH), assisted by a research student assistant. Both SS and LH attended various courses on and have previous experience with qualitative research. Given this experience, there may have been preconceived notions regarding VR for CMP. We aimed to reduce potential biases by fostering open discussions and critical reflections throughout data collection and analysis. None of the participants had previous relationships with any of the researchers conducting and analyzing the focus group. The topic list used for this focus group is added in Multimedia Appendix 3.

Outcomes

The outcome measures are shown in Table 1. The TIIM app (University of Twente, Enschede, the Netherlands) was used to collect demographic information, diary measures, and weekly questionnaires.

Table . Overview of outcome measurements.

	Pre	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Post
Patient characteristics	✓							
Diary measures		✓	✓	✓	✓	✓	✓	
Weekly questionnaires		✓	✓	✓	✓	✓	✓	
Wearable data		✓	✓	✓	✓	✓	✓	
VR[a] parameters			✓	✓	✓	✓		
Feasibility								✓

[a]VR: virtual reality.

Diary Measures

The daily diary questions consisted of 4 questions, based on the IMMPACT (Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials) recommendations for chronic pain clinical trials [24]: pain intensity (ie, what score would you give your pain today?), pain interference (ie, how burdensome was your pain today?), physical functioning (ie, to what extent did your pain restrict you in doing daily activities today?), and emotional functioning (ie, how was your mood today?). All questions were scored on a 0 (lowest) to 10 (highest) scale. A recent study showed that daily measures of pain and pain-related variables are both valid and reliable [25].

Weekly Questionnaires

Every week, participants were asked to answer 3 questionnaires to measure pain self-efficacy (Pain Self-Efficacy Questionnaire [PSEQ]) [26], pain acceptance (Chronic Pain Acceptance Questionnaire [CPAQ]) [27], and pain coping (Pain Coping Inventory [PCI]) [28]. These questionnaires were the Dutch translation of the original questionnaires, and all were shown to have adequate reliability and validity [29-31].

Wearable Outcomes

The following outcomes were measured using the wearable: physical activity (ie, daily steps), sleep quality, and stress. Daily sleep quality was scored from 0 (worst sleep quality) to 100 (best sleep quality) based on multiple factors, including sleep duration, stress score during sleep, and restlessness. Daily stress was measured using Garmin's stress level from 0 (lowest stress level) to 100 (highest stress level), which is based on the participant's heart rate variability (HRV). More information about the construction of sleep quality and stress as outcome measures in this study can be found in the Garmin manual [32].

Other Outcomes

The following patient characteristics were asked at baseline: age, gender, duration of CMP, comorbidities, pain location, pain medication use, expectation of intervention, occupational situation, education level (based on [33]), and experience with VR for treatment and entertainment.

VR-related parameters that were monitored included usage and module of the VR intervention.

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The feasibility of the intervention was explored using usability data (ie, number of minutes used per day) and a semistructured postintervention focus group with patients who received the intervention.

Statistical Analysis

The results of the SCED study were examined using a combination of statistical and visual analyses [34,35]. Phase A1 of each individual participant was observed to determine a stable personal control to note any revealing alterations for the outcome variables measured in phase B. Both within-phase and between-phase analyses were performed and checked for patterns within participants. To determine changes in outcome variables in SCED studies, it is recommended to use the following factors to interpret the data: (1) raw data, (2) central tendency, (3) trend, (4) variability, (5) point of change, and (6) overlap region [15]. All visual plots were constructed using the Shiny SCDA web application [36,37]. Besides this visual analysis, outcomes of the diary questions and wearable data were statistically analyzed using the Tau-U nonoverlap method [38], using a web-based calculator [39]. Effect sizes for Tau-U were interpreted as small (0-.65), medium (.66-.92), or large (>.92) [38]. To gain insight into the relationship between pain-related variables during the intervention, outcomes of the weekly questionnaires were compared on an individual level using the Reliable Change Index (RCI). The RCI was calculated using the pretreatment and posttreatment scores and was considered reliable at 1.96 or more [40]. Clinically important differences in pain intensity were examined between pre- and postintervention, in which a reduction of ≥30% or 2 points was considered clinically important [41]. The recording of the focus group, which had a duration of 50 minutes, was transcribed using Amberscript. This transcript was analyzed using inductive thematic analysis with Atlas.ti (version 24), based on the 6 steps proposed by Braun and Clarke [42]: (1) (re-)read transcript to familiarize with the data, (2) generate initial codes, (3) combine codes into themes, (4) review themes, (5) define themes, and (6) report findings. These steps were completed by 2 researchers (SS and LH) and discussed until consensus was reached. Finally, all authors agreed on the final themes and results identified during this process.

Results

Patient Characteristics

A total of 9 participants enrolled in this study, of which 7 completed the study (Table 2). In addition, 1 participant stopped due to being too busy and 1 participant completed <50% of the questionnaires and was therefore excluded from the analysis. The 7 participants who were included in the analysis provided a median of 280 (range 241 - 315) data points per participant. None of the participants had previous experience with VR. No adverse events were reported by any of the participants from using the VR intervention.

Table . Demographics of participants (n=7).

Participant	Age (years)	Gender	Highest level of education	Occupational situation	Pain duration (years)	Pain location	Medication use	Expectancy[a]
1	31	Woman	Higher	Part-time	1	Foot, ankle	Yes	6
2	55	Man	Lower	Full-time	17	Legs, hands	Yes	5
3	45	Woman	Middle	Part-time	5	Wrist, shoulder, back	Yes	4
4	31	Woman	Middle	Unemployed	7	Generalized	No	6
5	61	Woman	Lower	Part-time	30	Back, hip	Yes	6
6	52	Woman	Higher	Full-time	3	Back, shoulders, neck	Yes	5
7	37	Woman	Higher	Part-time	4.5	Back, pelvic	Yes	6

[a]Scored from 0 (lowest expectancy) to 10 (highest expectancy).

Visual Analysis

Results of the visual analysis of the diary data showed that patients responded differently to the intervention, as discussed below per outcome variable. The results of the 4 diary outcome measures are presented in Figures 1 and 2 and Multimedia Appendix 4, in which the phases A1 (day 1 - 7, no intervention), B (day 8 - 35, intervention), and A2 (day 36 - 42, no intervention) are presented on the x-axis and scores from 0 (lowest) to 10 (highest) are presented on the y-axis.

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Figure 1. Visual analysis of diary data on pain intensity (see clearer version in Multimedia Appendix 5).

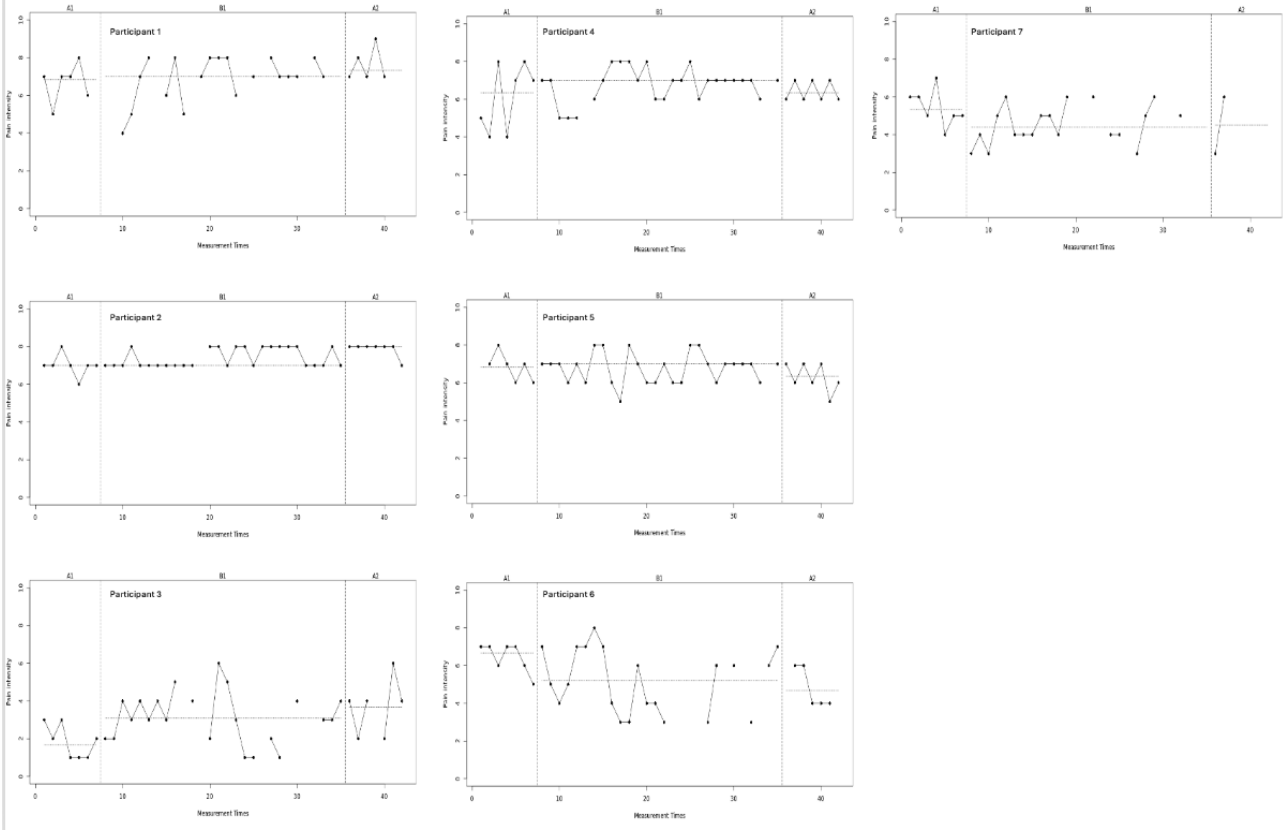
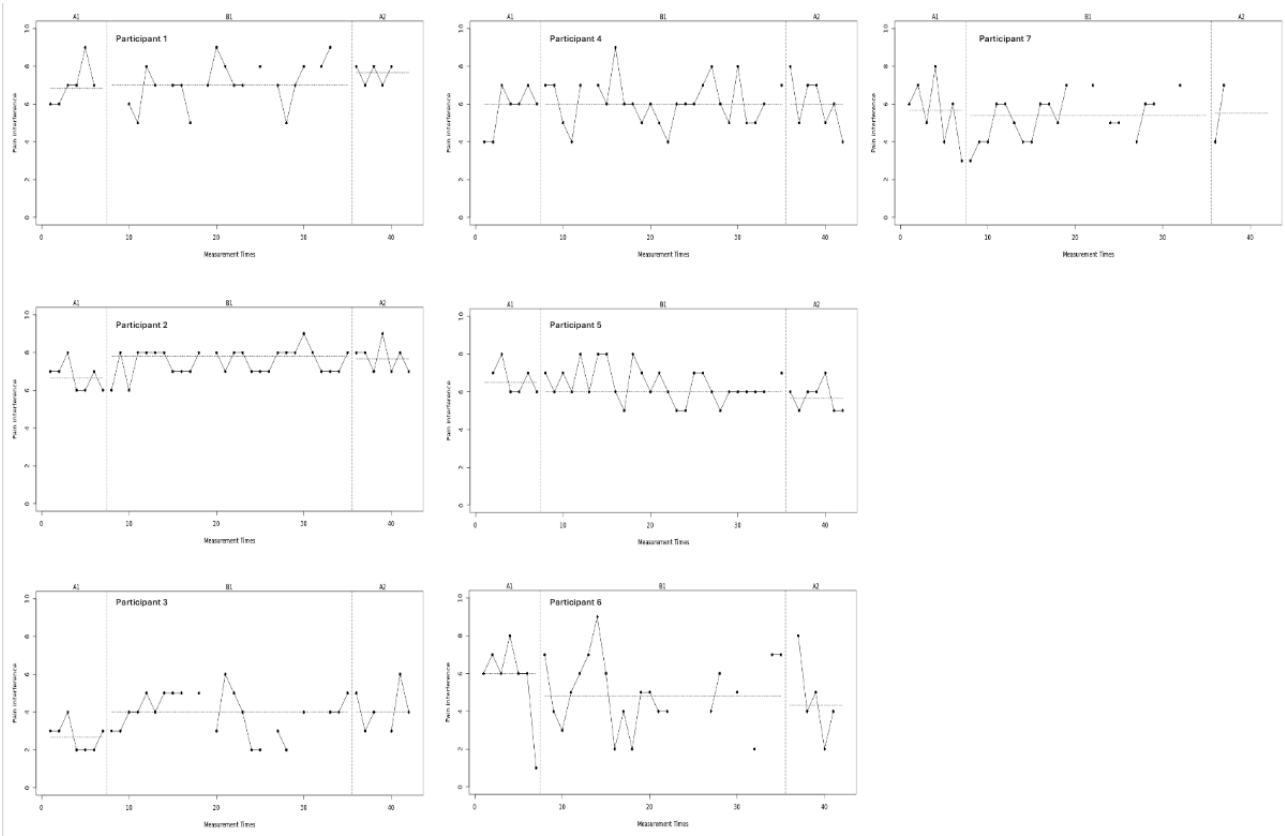


Figure 2. Visual analysis of diary data on pain interference (see clearer version in Multimedia Appendix 6).



Pain intensity scores (Figure 1) remained relatively consistent through phase A1, B, and A2. However, some participants seem to report somewhat lower scores during phase B compared with phase A1 (eg, participant 6 from mean phase A1 6.4, SD 0.8, to mean phase B 5.1, SD 1.7), while others report higher scores (eg, participant 3 from mean phase A1 1.9, SD 0.9 to mean

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phase B 3.3, SD 1.4). Furthermore, it is notable that most participants reported substantial variability within proximate measurement moments.

Analysis of the pain interference outcome (Figure 2) showed that patients reported fairly stable scores on central tendency. Some participants showed minor improvement between phases (eg, participant 2 from mean phase A1 6.7, SD 0.8, to mean phase B 7.5, SD 0.7), while others showed some deterioration (eg, participant 5 from mean phase B 6.4, SD 0.9, to mean phase A2 5.7, SD 0.8). In addition, it should be noted that pain interference scores show much likeness to pain intensity scores.

Results on physical functioning (Multimedia Appendix 4) showed that central tendency does not seem to alter too much between phases, similar to the results on pain intensity and pain interference scores. Variability within patients seems to be similar to previously reported outcome measures as well, except for participant 3 who shows large variability within proximate measurement times (eg, day 23: 2; day 24: 10; day 25: 2).

Finally, emotional functioning scores (Multimedia Appendix 4) were relatively high in most participants (mean 7.1, SD 1.5, compared with mean pain intensity 5.9, SD 1.8, pain interference 5.9, SD 1.8, and physical functioning 5.4, SD 1.7). Trend between phases seemed to be improving for some participants (eg, phase A1 of participant 7), while the opposite occurred in other participants (eg, phase A2 of participant 4). Variability seemed to be lower compared with previously discussed outcome measures in most participants.

Statistical Analysis

Analysis of the daily diary and wearable data using Tau-U, as shown in Table 3, showed no statistically significant difference in any of the outcome measures. In addition, no clinically important reductions in pain intensity (ie, reduction of pain intensity score of ≥30% or ≥2 points) were found. Results of the statistical analysis of the weekly questionnaires using the RCI (Table 4) showed no reliable change on any of the questionnaires for any of the participants. More detailed information about the results of the wearable data and weekly questionnaires can be found in respectively Multimedia Appendix 7 (individual scores on steps, stress, and sleep) and Multimedia Appendix 8 (Group scores on weekly questionnaires). Median VR use was 37.5 minutes per week (range 7.8 - 78.4).

Table . Statistical analysis of diary and wearable data.

	Tau-U	95% CI	*P* value
Pain intensity	−0.011	−0.16 to 0.14	.88
Pain interference	−0.013	−0.16 to 0.13	.87
Physical functioning	−0.091	−0.24 to 0.06	.23
Emotional functioning	−0.021	−0.17 to 0.13	.78
Steps	0.013	−0.14 to 0.17	.87
Stress	−0.075	−0.23 to 0.09	.36
Sleep	0.082	−0.08 to 0.24	.32

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Table . Statistical analysis of weekly questionnaires.

	Participant						
	1	2	3	4	5	6	7
PSEQ[a]							
Pretreatment, mean (SD)	43 (0.7)	31 (3.5)	42 (4.2)	21 (8.5)	37 (4.9)	23 (2.8)	27 (0)
Posttreatment, mean (SD)	38 (2.8)	36 (0)	47 (2.1)	23 (2.1)	45 (1.4)	18 (2.1)	29 (3.5)
RCI[b]	−1.05	1.05	1.05	0.42	1.68	−1.05	0.42
CPAQ[c]							
Pretreatment, mean (SD)	23 (0)	32 (0.7)	31 (0.7)	20 (0.7)	29 (1.4)	15 (1.4)	18 (5.7)
Posttreatment, mean (SD)	28 (1.4)	31 (3.5)	31 (2.8)	23 (0)	29 (1.4)	15 (2.1)	20 (2.1)
RCI	0.74	−0.15	0	0.45	0	0	0.30
PCI[d] active							
Pretreatment, mean (SD)	31 (0.7)	31 (1.4)	31 (1.4)	29 (0.7)	26 (0.7)	28 (0.7)	30 (1.4)
Posttreatment, mean (SD)	28 (1.4)	28 (0)	34 (0)	26 (0)	27 (2.8)	23 (1.4)	30 (0.7)
RCI	−0.84	−0.84	0.84	−0.84	0.28	−1.40	0
PCI passive							
Pretreatment, mean (SD)	40 (1.4)	44 (5.7)	42 (0)	64 (2.8)	46 (3.5)	49 (0.7)	51 (4.2)
Posttreatment, mean (SD)	43 (4.2)	44 (0.7)	36 (.7)	59 (1.4)	44 (0.7)	45 (0)	55 (1.4)
RCI	−0.38	0	0.77	0.64	0.26	0.51	−0.51

[a]PSEQ: Pain Self-Efficacy Questionnaire.

[b]RCI: Reliable Change Index.

[c]CPAQ: Chronic Pain Acceptance Questionnaire.

[d]PCI: Pain Coping Inventory.

Focus Group Analysis

Participants 4, 6, and 7, as described in Table 2, participated in the postintervention focus group. The other participants were not able to participate because they were too busy (with their pain rehabilitation program) (n=3), and did not feel well on the day of the focus group (n=1). Based on the analysis of the focus group, the following three themes were identified: (1) experiences of CMP patients with VR, (2) feasibility of VR, and (3) VR in CMP rehabilitation.

Theme 1: Experiences of CMP Patients With VR

Participants found the VR program attractive to use and valued the intuitive nature of the intervention. Furthermore, they reported several positive effects of the VR intervention, including feelings of self-efficacy, more knowledge about (chronic) pain and focus shifting. Although, these effects were not substantial and patients had to get used to using VR, as it demanded both their time and effort.

> *And it provided me with insights about how chronic pain works.* [Participant 7]
>
> *My focus shifted away from the pain and went more towards the game or killing those monsters, which was a lot of fun. And then you notice that it does something with the pain.* [Participant 6]
>
> *And then you still [use VR] while you are actually already tired and in need of a bit of a rest.* [Participant 4]

Theme 2: Feasibility of VR

Participants perceived the VR intervention as feasible. They found it easy and comfortable to use at home, the instructions were clear, and it was attainable to use daily.

> *And we received clear instructions beforehand, so then it's just plug and play, you know.* [Participant 4]
>
> *Yes, I think I actually liked using it at home first, instead of somewhere else.* [Participant 6]

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Theme 3: VR in CMP Rehabilitation

VR helped participants bridge the waiting time, but participants valued it more as an addition to their treatment rather than a substitution.

> *It's more of an addition, a good addition, a meaningful addition.* [Participant 6]

Some participants mentioned it might be valuable to provide the VR intervention not only during the waiting list period but also during the pain treatment they were on the waiting list for. Furthermore, it is important to consider the individual process and whether a patient is open to working on the topics addressed in the VR intervention.

> *…that it would be even more effective during pain treatment, it would be even stronger, because you are already more involved in it and you can also ask for feedback immediately, for example from one of your therapists, if you have any questions.* [Participant 7]

> *It [the VR intervention] raised some internal conflict, but I can really understand that it could be very helpful for patients who are further in their process.* [Participant 4]

In the future, patients would recommend to receive VR not on a daily basis, but maybe 2 or 3 times a week, in between the days of the pain rehabilitation program.

Discussion

Principal Findings

The aim of this study was to gain insight into the influence of VR on pain-related variables and evaluate the feasibility and general experience of this intervention. Analyses of the reported measures showed no clinical and statistically significant differences. Our results imply that the provided intervention did not influence the outcome measures used in this study. This was supported by the visual analyses, which showed that some participants somewhat improved after the intervention on several outcome measures, but worsened on different outcome measures. However, results of the focus group showed that patients qualitatively reported a positive perspective and experienced the intervention as feasible.

Comparison to Previous Work

The results of this study are comparable to other studies that provided the VR intervention, Reducept. A previous study that examined the effect of Reducept for patients with CLBP who were on a waiting list to receive pain treatment [9], showed no significant between-group results on the primary and most other outcome measures, except for opioid use, daily worst, and least experienced pain intensity. It should be noted that the patient sample in both their and our study were patients with severe and complex symptoms. They were referred to secondary pain care, with for example a median pain duration of 5 years in our sample. Previous studies showed that a longer duration of pain complaints was associated with a worse prognosis [43,44] and diminished responsivity to treatment [45]. As suggested before, this specific stand-alone VR intervention might therefore be more suitable for CMP patients with less complex complaints [17].

This study by de Vries et al [17] found somewhat more promising results when they conducted a SCED study among patients with CLBP where they received 9 to 12 45-minute sessions of the VR intervention [17]. Results of their study showed that Reducept might be able to induce clinically relevant reductions in pain intensity and other pain-related outcomes in some patients [17]. These patients were not on a waiting list to receive other pain treatment and received the intervention supervised in the hospital, which might have increased effectiveness [46]. Other interventions that used a stand-alone at-home VR intervention reported clinically meaningful results [47-49], but patients were (1) not on a waiting list to receive other pain treatment and (2) received a more extensive intervention (both in duration and content). A waiting list period is known to possibly deteriorate pain complaints [8]. A meta-analysis among psychotherapies even showed that waiting lists might be regarded as a nocebo condition since patients might, for example, feel the need to remain their complaints to be able to start the pain treatment they are on the waiting list for [50]. In addition, it might be possible that the waiting list period is not the best time to provide VR. This was mentioned in our focus group, and previous research showed that it is also possible to extend secondary care for CMP patients with VR as an additional treatment option [51,52]. In regard to the content of the VR module, it might be possibile to supplement this with, for example, personalized exercise therapy as was done in previous VR interventions for CMP [51,53,54]. Finally, the dosage of the VR intervention might be a point of interest, as the study by de Vries et al [17] found different results from this study while using another dosage of the same intervention. The intervention duration in this trial was 4 weeks, while for behavioral CMP interventions, a duration of 6 to 10 weeks is advised [55], which implies that the intervention did not last long enough. Future studies on VR for CMP should, therefore, study the optimal timing, (personalized) content, and dosage of VR interventions for the most fitting patients.

Results of our study showed a discrepancy between the analyses of quantitative outcome measures and qualitative measures. This is congruent with the qualitative evaluation [22] of the trial that was discussed before [9]. They reported that the VR intervention positively affected how patients' health was experienced, provided patients with more control over their pain, and helped patients accept and understand pain. This is supported by other studies in which patients did not report significant differences in, for example, quality of life or pain intensity measured using questionnaires but mentioned positive benefits during an oral evaluation after their VR intervention [17,56]. This discrepancy could partially be explained by social-desirability bias, as patients might want to portray a more positive impression of the intervention for the researcher who is interviewing them [57]. In addition, it might be possible that nonoptimal quantitative outcome measures were used for this VR intervention, and softer outcomes like values (eg, autonomy) or more proximate outcomes (eg, knowledge about CMP) should be examined as well, as was suggested previously [14].

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Strengths and Limitations

One of the strengths of this study was the use of a heterogeneous sample of patients with ranging ages (31-61 years), pain duration (1-30 years), and type of pain complaints. In addition, a rich dataset with multiple subjective (ie, daily diary, validated questionnaires, and focus group) and objective (ie, wearable) outcome measures was used, which was analyzed both visually and statistically. In line with SCED study recommendations, at least 5 data points per phase were collected [58].

This study had several limitations. First, the nature of the study design is characterized by a smaller sample size, which came with risks of selection-bias of specific patients and hindered generalizability of study results. Second, treatment fidelity varied between participants, and not all participants used the VR intervention as much as prescribed, which could have diminished the intervention effect. This problem was mentioned in other VR interventions for CMP as well [48,53], while it is known that repetition is key in, for example, PNE [59]. However, it should be noted that treatment fidelity varies outside a study design, and therefore, this study reflects a real-world situation. Third, we conducted only 1 focus group with 3 participants who provided an insight into the intervention feasibility. Given the limited sample size, these results should be interpreted with caution. However, a more in-depth analysis of qualitative data, possibly with one-on-one interviews instead of focus groups, of participants' experience with VR in a larger study sample would be interesting, to learn more about possible working mechanisms and administration best practices of VR for CMP, which could further improve this intervention.

Future Directions

The results of this study suggest implications for clinical and theoretical practice. It seems that this stand-alone VR intervention for patients with CMP on a waiting list for secondary care does not influence pain-related complaints. However, in the right dose, setting, and timing it might be more effective, as previous research, for example, suggested that VR interventions for CMP might be more effective for younger patients [60]. To further inform trial and intervention design, other relevant pain-related outcomes (eg, catastrophizing) and medication use could be investigated, as these were found relevant in previous VR for CMP studies [9]. In addition, future studies could explore prognostic patient characteristics to identify patients who would respond better or worse to therapeutic VR for CMP. To further study the effectiveness of the (improved) intervention and complement the findings of this study, a randomized controlled trial (RCT) is warranted, in which a control group that receives usual care should be included. This RCT should both focus on the short-term results and include an analysis of the complete pain treatment trajectory. Furthermore, subgroup analyses are needed to examine for which patients VR is effective.

The results of this study showed that this stand-alone immersive VR intervention for patients with CMP on a waiting list did not seem to alter pain-related outcomes. Patients reported good feasibility and general positive experience of the intervention and these outcomes can inform further intervention and trial design.

Acknowledgments

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Data Availability

The datasets generated during this study will not be publicly available but will be available upon reasonable request to the corresponding author.

Authors' Contributions

SS was the principal investigator of this study and drafted the first version of the manuscript. LH conceptualized and designed the study, reviewed and revised the manuscript, and performed supervision. SS, RA, JB, NMDO, RTR, and MS supported recruitment of patients and reviewed and revised the manuscript. MT conceptualized and designed the study, reviewed and revised the manuscript, and supervised SS. All authors contributed to the manuscript and approved the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Single-Case Reporting Guideline in Behavioural Interventions (SCRIBE) checklist.
[DOCX File, 19 KB - xr_v2i1e58784_app1.docx]

Multimedia Appendix 2
Consolidated Criteria for Reporting Qualitative Research (COREQ) checklist.
[DOCX File, 26 KB - xr_v2i1e58784_app2.docx]

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Multimedia Appendix 3
Topic list focus group.
[DOCX File, 13 KB - xr_v2i1e58784_app3.docx]

Multimedia Appendix 4
Visual analysis of diary data on physical and emotional functioning.
[DOCX File, 242 KB - xr_v2i1e58784_app4.docx]

Multimedia Appendix 5
Clearer version of "Visual analysis of diary data on pain intensity."
[PPTX File, 118 KB - xr_v2i1e58784_app5.pptx]

Multimedia Appendix 6
Clearer version of "Visual analysis of diary data on pain interference."
[PPTX File, 124 KB - xr_v2i1e58784_app6.pptx]

Multimedia Appendix 7
Individual scores on steps, stress, and sleep.
[DOCX File, 371 KB - xr_v2i1e58784_app7.docx]

Multimedia Appendix 8
Group scores on weekly questionnaires.
[DOCX File, 17 KB - xr_v2i1e58784_app8.docx]

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Abbreviations

ACT: acceptance and commitment therapy
CBT: cognitive behavioral therapy
CE: Conformité Européenne
CLBP: chronic low back pain
CMP: chronic musculoskeletal pain
COREQ: Consolidated Criteria for Reporting Qualitative Research
COREQ: Consolidated Criteria for Reporting Qualitative Research
CPAQ: Chronic Pain Acceptance Questionnaire
HMD: head-mounted display
HRV: heart rate variability
IMMPACT: Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials
PCI: Pain Coping Inventory
PNE: pain neuroscience education

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PSEQ: Pain Self-Efficacy Questionnaire
RCI: Reliable Change Index
RCT: randomized controlled trial
SCED: single-case experimental design
SCRIBE: Single-Case Reporting Guideline in Behavioural Interventions
VR: virtual reality

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The Feasibility and Acceptability of a Stand-Alone Virtual Reality Headset on Perceived Pain and Anxiety During Bone Marrow Biopsies: Mixed Methods Pilot Study

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Abstract

Background: Virtual reality (VR) is an emerging technology that provides an immersive user experience and has the ability to distract patients from the negative or painful experiences commonly associated with medical procedures. Bone marrow biopsies are medical procedures where a needle is inserted into the bone and a syringe is used to withdraw the liquid bone marrow. They are performed to diagnose and monitor disorders affecting the blood, often as part of care for hematology and patients with cancer.

Objective: The purpose of this pilot study is to assess the feasibility of VR as an adjunctive therapy to alleviate the perception of pain and anxiety in patients receiving bone marrow biopsies.

Methods: This pilot study enrolled 60 adult participants receiving a bone marrow biopsy to assess the acceptability and feasibility of VR to impact reported pain and anxiety levels compared to the participants' baseline measurements preoperatively. They were randomly assigned to "control"/non-VR intervention (n=30) and "experimental"/VR groups (n=30). The "experimental"/VR group used the Meta Quest 2 headset (Meta) with original VR content developed for this study. Participants completed a survey adapted from a standardized verbal numerical rating scale to rate their pain and anxiety levels before and after the bone marrow biopsy. Measurements such as procedure length, patient vitals, and experience were also gathered from both study groups.

Results: Results indicated that participants had no significant differences in their heart rate, respiration rate, and blood oxygen saturation levels between the 2 groups. Participants in the VR group (n=30) had a significantly shorter procedure length than the control group (n=30) with a 25% time reduction (P=.02). Participants in the VR group (mean 4.29, SD 1.19) were significantly more likely to rate the distraction as effective (P<.001) and report they would repeat the procedure (mean 4.32, SD 1.05; P<.001). Finally, participants in the VR group (mean 2.13, SD 1.26) had significantly lower levels of anxiety during the procedure (P<.001) and felt significantly more comfortable after the procedure (mean 4.45, SD 1.12; P<.001).

Conclusions: This investigation encourages the acceptability of using VR intervention for patients undergoing bone marrow biopsies. Further, the length of procedures was found to be shorter when compared to the control group, supporting the feasibility of the technology for clinical management. These novel interventions can provide distraction-based therapy that is noninferior to the standard of care and provide enjoyable user experiences that reduce the perceived pain and anxiety of nonsedated medical procedures.

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KEYWORDS

virtual reality; bone marrow biopsy; oncology; pharmacologic pain management; pain management

Introduction

Standard pain management protocols in adult medicine settings, hospitals, or clinics, typically rely on the use of pharmacotherapies such as acetaminophen, nonsteroidal anti-inflammatory drugs, analgesics, and opioids to alleviate acute pain [1]. Although these forms of treatment can be effective, there are growing concerns surrounding the potential health risks associated with the use of certain pharmacotherapies, such as opioid addiction, across patient populations [2]. As a result, there is a growing interest in reducing the use of pharmacotherapy for the treatment of acute pain in favor of nonpharmacologic options [3]. However, there are few

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alternative options for providing nonpharmacologic therapy in adults, which often results in inadequate pain control [4]. There is a need to find feasible and acceptable adjunct forms of pain management and anxiety reduction in a hospital or clinic setting.

Distraction techniques used by hospital staff help patients cope with injuries, hospitalization, or illness and differ based on each patient's needs and preferences [5]. Some common techniques used to distract from chronic pain include controlled breathing, guided imagery, and relaxation [6]. Passive techniques such as auditory distraction and television have been used to distract from acute pain resulting from routine procedures [7]. Studies for each of these different techniques over the years found some positive, but mostly mixed results [8]. Thus, there is still limited evidence demonstrating the effectiveness of distraction [9]. Moreover, there is no conclusive study suggesting that one technique supersedes others since each patient has different preferences, medical situations, behavioral needs, and developmental needs.

Virtual reality (VR) is an emerging technology that provides an immersive user experience [10]. These immersive VR experiences show promise as a tool that can reduce perceived pain and anxiety related to acute pain in emergency rooms or other clinical settings by lessening the vividness of memories [11]. One study has even observed that immersive VR was more effective than standard care in ameliorating pain among pediatric patients undergoing venipunctures [12]. It is theorized that immersive VR draws the patient's attention away from aversive, or painful, stimuli by keeping their focus on something more engaging [13]. A study published in 2023 by Alaniz et al [14] found VR to be an underused intraoperative tool that enhances the overall patient experience in the emergency room. Furthermore, another study by Sabinash [15] reported positive findings with this technology, which are tempered by the limitations of current research, but VR still holds great potential. The stand-alone headset's hardware offers an affordable alternative that can potentially provide a nonpharmacologic treatment for acute pain management and anxiety reduction [16]. A study published in Virtual Worlds found that it is likely to see the widespread implementation of VR in health care in the coming decade [17]. With recent advancements, VR technology is used in numerous settings, but limited research has been done thus far to show how effective it is [18].

The purpose of this pilot study is to evaluate the feasibility and acceptability of using VR adjunctively as a nonpharmacological distraction method for bone marrow biopsies to reduce perceived anxiety and pain in an oncology ward setting. The information gained will help to design future studies needed to ensure the efficacy and reliability of the devices.

Methods

Design Overview

This pilot acceptability and feasibility study was performed at the University of Florida (UF) Shands Cancer Hospital to assess VR as a relaxation and distraction tool for patients receiving a bone marrow biopsy procedure. We used a mixed methods design, in which trained research assistants identified and determined eligibility of patients admitted to the UF Health Division of Hematology & Oncology Ward in coordination with medical staff. Participants were randomly assigned to the control group and experimental group through a random number sequence to determine group allocation. No stratification was used in this process. The control (or non-VR intervention) group did not receive any special distraction in addition to local anesthesia, following conventional clinical practice for managing discomfort. Local anesthesia is defined as 5‑10 mL of lidocaine 1% (10 mg/mL) without epinephrine administered to patients for bone marrow biopsies, according to the UF Health Shands Hospital protocol. Approximately 1‑2 mL skin wheal (intradermal) was used to numb the skin, followed by a 2‑3 mL subcutaneous infiltration to numb deeper tissue, and then a 2‑5 mL periosteal infiltration for the bone surface. No additional nonpharmacological distraction methods were implemented in this group. Data regarding patient vitals, procedure length, patient feelings before and after the procedure, and patient experiences with the procedure were compared between participants assigned to the VR and control groups. The 2 groups were compared using independent *t* tests with Cohen *d* measure of effect size. For any measure taken before and after the procedure, the difference between the 2 was calculated and used to compare the groups for the *t* tests.

Training Protocol

Research assistants underwent a 4‑ to 5-week training period covering all aspects of the patient intervention, including preprocedural preparation, informed consent, intervention administration, and postprocedural procedures. Training emphasized appropriate patient interaction, including how to explain and review consent and procedural forms. In addition, research assistants received instruction on infection control measures, such as proper sanitization of the VR equipment. These measures for the VR headsets included the use of Super Sani-Cloth Germicidal Disposable Wipes to thoroughly disinfect the headset and controllers before and after each patient's use. In addition, research assistants were instructed to wash their hands before and after each patient interaction to minimize the risk of cross-contamination. The final 2 weeks of training focused on VR equipment operation, troubleshooting technical issues, and ensuring a smooth patient experience.

Participants

Participants were recruited between February 2021 and February 2024 from the UF Health Oncology & Hematology ward. A total of 93 patients were initially screened for eligibility, of whom 60 patients met the inclusion criteria and were enrolled in the study, with 30 randomized to the VR group and 30 to the control group. Participants were included according to the following criteria: have a scheduled bone marrow biopsy, aged more than 18 years, and be able to physically wear and tolerate the VR headset. Participants were excluded if they had nausea or vomiting upon admission, required urgent procedures or were otherwise deemed unstable by hospital staff, had a condition that prevents the use of VR technology such as epilepsy, or a facial or scalp wound, had any visual, hearing, or cognitive impairments that would limit their ability to take part in the study, or if they could not read, speak, or write in English. The

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demographic characteristics of the participants are shown in Table 1. The majority of participants were male, the median age was 61.5 years (IQR 53 - 68), the racial composition was 75% White with approximately 17% Black (10/60 participants) and 8% Latino (5/60 participants) enrolled, and 63% (38/60 participants) of them reported some familiarity with VR.

Table . Demographic information and familiarity with VR[a].

Demographics	Total population (N=60)	Control (n=30)	VR (n=30)	Statistical test results for differences between control and VR groups, *t* test or chi-square (*df*)	*P* value
Age (years), median (IQR)	61.5 (53-68)	65 (58.5 - 69.5)	58 (48-64)	1.31 (57.18)[b]	.92
Gender, n (%)				0.16 (1)[c]	.69
Male	36 (60)	16 (53)	19 (63)		
Female	24 (40)	14 (47)	11 (37)		
Race, n (%)				1.86(4)[c]	.76
White	45 (75)	23 (77)	22 (73)		
Black	10 (17)	4 (13)	5 (17)		
Latinx	5 (8)	3 (10)	3 (10)		
VR familiarity, n (%)	38 (63)	19 (63)	19 (63)	0.78 (1)[c]	.78

[a]VR: virtual reality.

[b]*t* test.

[c]Chi-square test.

Distraction-Based VR Intervention

The “HealthPointXR” app (Gainesville, Florida), developed for this study, was used to provide distraction and relaxation for participants enrolled in the experimental group. The “HealthPointXR” app was developed by Drew Gill as part of a UF undergraduate engineering organization by the name of Dream Team Engineering. There are no financial disclosures related to the development or commercialization of this app at this time. The HealthPointXR game is currently an unlicensed, private project owned by Dream Team Engineering as per GitHub for an unlicensed project “the default copyright laws apply, meaning that [the owner] retain[s] all rights to [their] source code and no one may reproduce, distribute, or create derivative works from [their] work.” The code is currently neither open source nor free, but contacting Dream Team Engineering via their website is encouraged for any usage. This study used a retrofitted Meta Quest 2 headset (Meta) with plastic straps and easily sanitizable materials. The VR device was selected based on affordability and quality to ensure its practicality and scalability in clinical settings. The Meta Quest 2 met these criteria, while the Apple Vision Pro was considered as a potential alternative. However, due to its recent market entry and significantly higher cost, it was not incorporated into this study. The Meta Quest 2 fits most head shapes and sizes. Tablets were connected to the headsets for research assistants to control and supervise the VR content in real time using an intuitive interface. The tablet and the VR headset were connected through a Bluetooth pairing and did not require internet or Wi-Fi connectivity. “HealthPointXR” VR game included an experience of a tranquil walking path through a natural environment where the user snaps photographs of wildlife passing by while being transported in a cart along a track. The user must take these different photographs when prompted to advance their journey. Users are also incentivized to follow the track closely through minimal head movements in order to receive points on the trip across the natural environment to further immerse the user. Soothing music and different sounding notifications provide auditory cues to engage the user.

For participants randomly selected to the experimental group, research assistants provided a standardized 5-minute tutorial on wearing the VR headset and fitting it properly for optimal user experience. The length of time required to fit the VR headset on participants was not factored into the total length of the procedure, as it was done during normally occurring time intervals prior to the bone marrow biopsy procedure. Figure 1 shows an example of the VR experience.

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Figure 1. "HealthPointXR" virtual reality experience.

Patient Vitals and Procedure

Patients in both the VR and the control group had their vitals, including heart rate, respiration rate, and blood oxygen saturation, recorded through a pulse oximeter during and after the procedure. These vitals were taken by the health care staff present at the time of the procedure, and research assistants collected these data from the health care staff after completion of the intervention. Procedure length was recorded on a stopwatch by the research assistants, who began measuring the procedure length as soon as the VR headset was placed on the patients. Timing concluded at the end of the medical procedure once the clinician completed the last component of the procedure.

Patient-Reported Emotional and Procedural Experience Measures

Patients in both the VR and the control group were asked the same questions regarding their feelings and experience with the procedure. Patients' feelings regarding the procedure were assessed by pain before and after the procedure, worry before and after the procedure, anxiety before and after the procedure, and comfort after the procedure. Feelings of pain were recorded using a verbal numerical rating scale from 1 to 10 before and after the procedure with higher values indicating higher feelings of pain. Feelings of worry were measured before and after the procedure using a scale from 1 to 5, with 1 indicating "not worried at all" and 5 indicating "extremely worried." Feelings of anxiety during the procedure were recorded on a verbal numerical rating scale from 1 to 5, with higher values indicating higher feelings of anxiety. Feelings of comfort after the procedure were evaluated using a 5-point scale from strongly disagree to strongly agree for the statement "I felt comfortable with the distraction."

Patients' experiences with the procedure were all assessed on a 5-point scale from strongly disagree to strongly agree. To measure awareness, patients were asked their agreement with the following statement: "I was very aware of the procedure I was receiving." To measure distraction effectiveness, patients were asked their agreement with "Using the distraction made me feel less worried about getting the procedure." Finally, for likelihood to repeat, patients were asked their agreement with "I would want to use the same distraction on medical procedures in the future."

Ethical Considerations

This study, which includes human participant research, was approved by the Institutional Review Board of the Florida Department of Health (IRB201900850). The informed consent forms, used in this study, provided participants with a description of the study, its qualitative and quantitative measures, potential risks and discomforts, and explicitly asked the patient to voluntarily agree to participate and allow their data to be collected. Study data are deidentified as all participants were assigned a numerical code. This code follows the format of OC001. Anonymity of all study subjects is ensured. No compensation of any sort was offered to human participants. This was stated in the informed consent form. No identification of individual participants is present in any images of this study or in any supplemental material.

Results

Patient and Procedure Summary Information

Figure 2 summarizes the patient's vitals and procedure duration between the VR and the control group. The patient's heart rate, respiration rate, and blood oxygen saturation were taken before and after the procedure. There were no significant differences in the change in vitals pre- and postprocedure between the VR and control group. The average procedure duration was significantly shorter in the VR group (mean 23.94, SD 9.72) compared to the control group (mean 31.94, SD 15.34; $t_{51}=-2.45$, $P=.02$, $d=0.62$).

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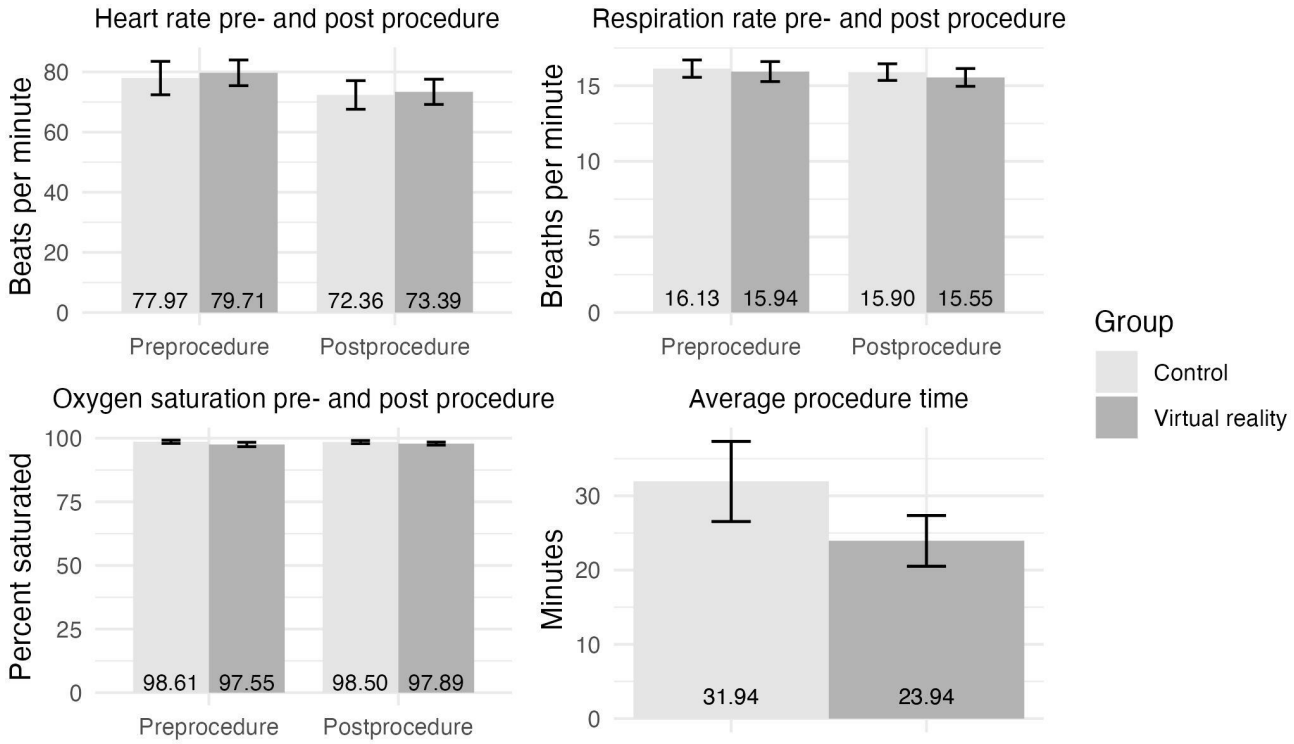
Figure 2. Summary of patient vitals and procedure length.



Patient-Reported Emotional Measures

Figure 3 summarizes patients' feelings before, during, and after the procedure between the VR and the control group. Patients were asked to indicate their feelings as explained in the Methods section, with higher scores indicating higher levels of pain, worry, anxiety, and comfort. The error bars represent 95% CIs, and the mean for each group is labeled at the bottom. Participants in the VR group (mean 2.13, SD 1.26) had significantly lower feelings of anxiety during the procedure compared to the control group (mean 3.42, SD 1.46; $t_{57}=-3.73$, $P<.001$, $d=0.95$). Participants in the VR group (mean 4.45, SD 1.12) had significantly higher feelings of comfort with the distraction compared to the control group (mean 2.10, SD 1.27; $t_{59}=7.73$, $P<.001$, $d=1.96$). There were no significant differences between the VR and control groups for pain and worry either before or after the procedure. In addition, there was no significant difference within either the VR or control group for the difference in pain or worry perception before and after the procedure.

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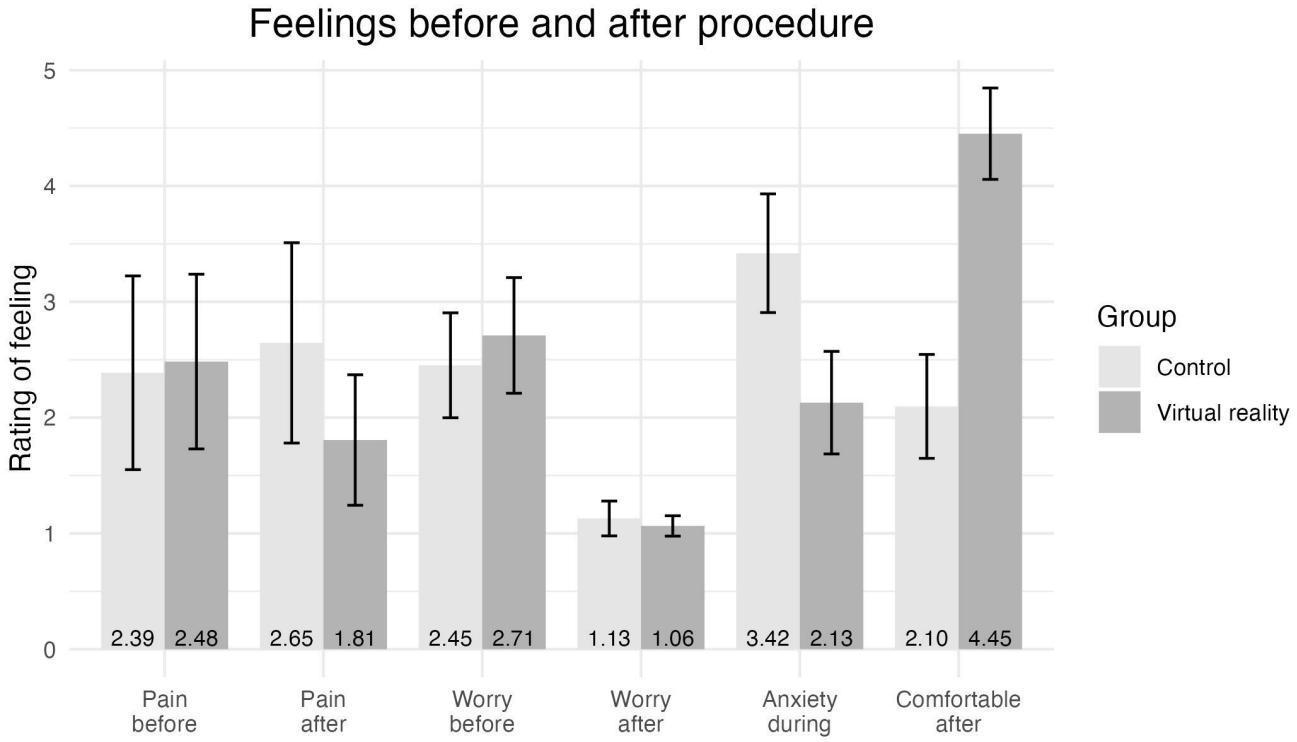
Figure 3. Differences in patient feelings before and after the procedure.



Patient-Reported Procedural Experience Measures

Figure 4 summarizes differences in patient experience during the procedure between the VR and the control group. Patients were asked to rate the statements on a scale of 1 to 5, with higher scores indicating a larger awareness of the procedure occurring, higher effectiveness of the distraction, and a greater likelihood to repeat the procedure. The error bars represent 95% CIs and the mean for each group is labeled at the bottom. Participants in the VR group (mean 4.29, SD 1.19) were significantly more likely compared to the control group (mean 1.55, SD 0.93) to rate the distraction as effective (t_{57}=10.14, P<.001, d=2.57). Participants in the VR group (mean 4.32, SD 1.05) were also significantly more likely compared to the control group (mean 1.81, SD 1.25) to indicate they would repeat the experience (t_{58}=8.60, P<.001, d=2.18). However, there were no significant differences between participants in the VR group (mean 4.45, SD 0.96) and the control group (mean 4.52, SD 0.85) of how aware participants were of the procedure occurring (t_{57}=−0.28, P=.78, d=0.07).

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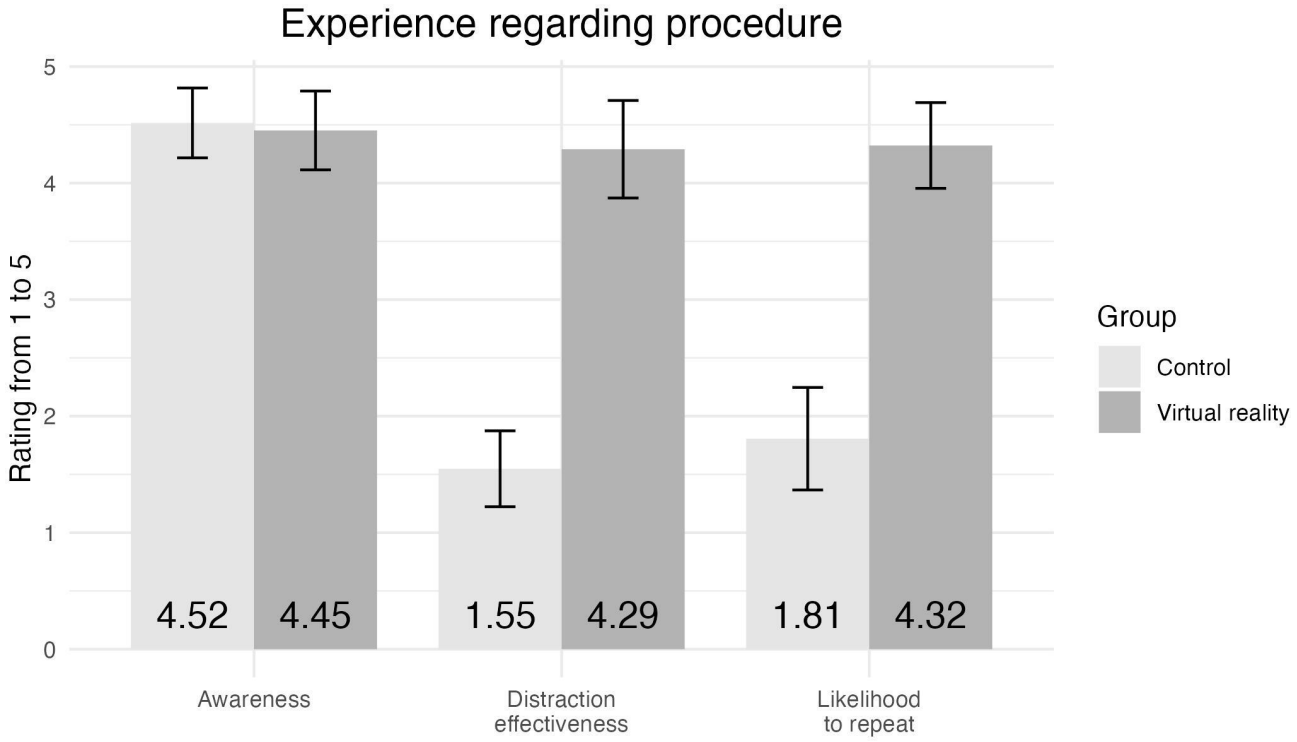
Figure 4. Differences in patient experience during the procedure.



Power Analysis

We conducted a post hoc power analysis using the *pwr* package in R to assess the statistical power of our independent samples *t* tests. Using the calculated effect sizes, we estimated the achieved power for each test assuming a 2-tailed *t* test with an alpha level of .05 and a sample size of 30 per group. The resulting power values ranged from 0.058 (d=0.07) to 1 (d=2.57). The estimated achieved power for 4 of the 6 independent samples *t* tests was above 0.95 ($d \leq 0.95$).

Discussion

Principal Findings

The results of this pilot study suggest that VR has a role in reducing anxiety and perceived pain in adult patients receiving bone marrow biopsy. Although this study is not designed to be statistically powered, a notable reduction in perceived pain was measured in the VR group, with a reduction of 0.7 in reported pain levels postoperatively compared to the control group's increase of 0.2 reported pain postoperatively on a 10-point scale. These findings paralleled those reported by Wong and Choi [12] when assessing patient perceptions of VR for pain relief in labor [19].

Anxiety levels before and after bone marrow biopsies were not significantly different in the VR group compared to the control group. Anxiety in patients with cancer can be triggered by a multitude of factors, as well as anticipation of pain associated with medical procedures [20]. VR might be slightly effective in reducing reported anxiety levels, although the complex combination of factors associated with the care of patients with cancer requires caution when interpreting the results of a tool used in an acute care application. This differs from similar studies that have reported marked changes in reported anxiety levels. A study by Fabi [21] reported that among 22 patients who used VR during chemotherapy, there was a significant decrease in perceived anxiety and duration of procedure compared to the control group.

Acceptability of VR in the hospital setting was supported by the patient experience findings and reinforced by the anxiety and perceived pain data collected during this study. The results of the surveys suggest a 2 - 3 point higher score in level of immersion, likelihood to use intervention again, and comfort level in the VR group compared to the control group using a 5-point scale. The majority of patients expressed a willingness to use VR as a distraction-based tool during their bone marrow biopsy. Furthermore, a study published by the *Journal of Internet Medical Research* in 2022 found VR beneficial for breaking up the monotony of treatment, providing an additional choice of activity, and in some instances a distraction from the treatment itself [22].

Measurements of feasibility for VR focused on the usability and comfort of the technology as well as its impact on the length of time for the medical procedure to be completed. To maintain methodological rigor, confounding variables were controlled as much as possible to ensure that any observed differences could be attributed primarily to the VR intervention rather than external factors. These confounding factors include standardizing the administration of lidocaine to 5 - 10 mL for bone marrow biopsies within the hospital's protocol, having the same clinician perform all the bone marrow biopsies throughout the course of this investigation, timing the procedure length to reflect the total length of the procedure as soon as a distraction method begins, that is when a VR program is turned on, before the procedure, as well as maintaining consistent informed consent and randomization practices for all participants. Consequently, the time differences observed in the

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results are attributed to the impact of VR. Notably, there was an 8-minute faster completion or 25% time reduction for completion of the bone marrow biopsy procedure among the VR intervention group (n=30) compared to the control group (n=30). The faster completion of the procedure occurred without any report of compromised quality of care, and these data provide a valuable clinical benchmark for the use of VR in the hospital setting, as it appears to improve the efficiency of providers while performing routine procedures. This surprising difference in procedure length is mostly attributed to the patients in the VR group being more composed and less tense at the beginning of the procedure, allowing for clinicians to more efficiently administer local anesthetic and perform the biopsy in a shorter amount of time. As the same clinician performed all of these bone marrow biopsies, clinician-to-clinician skill level was not a factor modulating the findings. The majority of the time was saved with the patient being immersed in the virtual world at the beginning of the procedure, which coincided with lower self-reported anxiety and pain ratings. It is important to note that the fitting of the VR headset on participants was performed during usual preparatory intervals prior to the biopsy procedure, and thus was not included in the recorded procedure time. The same size remains a limitation on these findings to differentiate them from being anecdotal as opposed to being powered, warranting the need for further investigation regarding time efficiencies and cost-effectiveness regarding the use of VR in minimally invasive procedures such as bone marrow biopsies.

The existing evidence to support the implementation of distraction-based VR therapy is still limited among patients with cancer receiving bone marrow biopsies [23]. This study provided insight into the novel application of a stand-alone VR headset. The results from this study indicate the use of VR as a noninferior adjunct tool that is acceptable and feasible for providing distraction and relaxation in adult patient populations undergoing bone marrow biopsy. Furthermore, these data add to building the evidence base for VR in medicine as part of innovative clinical practice involving digital therapeutics.

This study has several limitations, as the study was not designed to measure the impact of potential moderators on the outcomes. For example, the data cannot provide reliable information on the potential impact of age, gender, or pain tolerance of participants enrolled in the study. Another limitation of this study is the potential for selection bias, as participants were recruited exclusively from the UF Shands Oncology Ward in Gainesville, Florida. In addition, only patients undergoing the specific procedure of bone marrow biopsies were included, which may limit the generalizability of the findings to broader oncology populations or patients undergoing different procedures. The demographic and geographic constraints of the sample may also impact external validity, as factors such as regional health care access, socioeconomic status, and cultural background were not accounted for. The study design, sample size, and inability to double-blind the participants are also notable limitations that impacted the quality of data reported in this research. A review by Kouijzer et al [24] supports these considerations, as a lack of time and expertise on how to use VR in treatment, a lack of personalization of some VR apps to patient needs and treatment goals, or the gap in knowledge on the added value of VR in a specific setting were noted as limitations. In addition, the enrollment strategy could not control for the use of additional pain medication prior to the bone marrow biopsy that was self-prescribed by the patient prior to being approached regarding participation in the study. Furthermore, the study did not factor in medications that the patients are on or the full past medical history of participants to consider the impact of those factors on the participants' vital signs.

Conclusions

In conclusion, this pilot study's findings suggest that the use of an Oculus Quest 2 Headset with the "HealthPointXR" VR program can serve as a noninferior adjunct distraction-based therapy option for patients who are distressed when undergoing a bone marrow biopsy. Based on the parameters assessed, it is reasonable to determine that the implementation of VR improved anxiety levels and perceived pain and did not prolong clinical workflow on average. Further studies with greater statistical power and a larger scale could provide more robust evidence to support the routine application of this emerging technology to impact patients' experience during nonsedated, minimally invasive procedures.

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Authors' Contributions

AM and JW conceptualized and planned out the methodology of the study. AM and JW worked on the programming and software development of the virtual reality game. TW supervised the project. AM and SH carried out the investigation, and AM, SH, and KK wrote and edited the manuscript. KK analyzed the data, and AM and JW contributed to the interpretation of the results. All authors provided critical feedback throughout the study and helped shape the research and manuscript.

Conflicts of Interest

None declared.

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Abbreviations

UF: University of Florida
VR: virtual reality

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Integrating Extended Reality Into Primary Care Chronic Pain Programs via the REDOCVR Intervention: Real-World Implementation Feasibility and Usability Study

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Abstract

Background: Chronic pain management in public health services often struggles with limited engagement, emotional burden, and medication use. Extended reality (XR) shows promise in specialized settings, but evidence for codesign and integration into primary care remains limited.

Objective: This study aimed to examine the feasibility, usability, and real-world implementation of REDOCVR [RE (Reeducació), DOC (Dolor Crònic), VR (Virtual Reality)], an XR-supported psychoeducational program, and to explore preliminary clinical outcomes during its integration into chronic pain groups in public primary care centers.

Methods: This was a nonrandomized, hybrid type 2 phased implementation study conducted in 3 primary care centers in Catalonia, Spain. The intervention built on existing multidisciplinary psychoeducational chronic pain groups led by psychologists and physiotherapists. In collaboration with patients, XR modules were codesigned and incorporated to enhance mindfulness, cognitive reframing, and motor activation activities already established in routine care. In total, 8 weekly sessions included 15 - 20 minutes of this content, with a supervised medication tapering protocol included in later groups. Primary outcomes were implementation measures (adherence, tolerability, System Usability Scale, and satisfaction). Secondary outcomes included patient-reported clinical measures (Warwick-Edinburgh Mental Well-being Scale [WEMWBS], Hospital Anxiety and Depression Scale [HADS], Central Sensitization Inventory, and EuroQol – 5 Dimensions – 5 Levels) and medication changes, assessed at baseline, post-intervention, and 5-month follow-up.

Results: In total, 42 participants were enrolled, and 36 (85.7%) completed the intervention and all assessments. Adherence was high, and no serious adverse events occurred, with minimal cybersickness reported (5.6%). Patient usability was strong (mean 81.4, 95% CI 75.6 - 87.1), and overall satisfaction was high (mean 82.4, 95% CI 78.5 - 86.4). Professional usability was moderate (mean 59.1, 95% CI 51.6 - 66.5). Statistically significant improvements were observed in emotional well-being (Warwick-Edinburgh Mental Well-being Scale mean change 4.8, 95% CI 2.9 - 6.7; Cohen d=0.86), anxiety (HADS-A –2.5, 95% CI –3.8 to –1.2; Cohen d=0.66), and depression (HADS-D –1.6, 95% CI –2.5 to –0.7; Cohen d=0.62) (all P<.001). Mobility improved significantly (median change –1.0, 95% CI –1.0 to 0.0, P=.02), while Pain/Discomfort showed a nonsignificant trend (P=.08). Among tapering participants (n=22), mean use of benzodiazepines decreased by 71.7% and opioids by 41.8% at 5 months.

Conclusions: This study suggests that an XR-enhanced psychoeducational program can be incorporated into group-based chronic pain care within the public primary health care system. Exploratory improvements in emotional well-being, anxiety, depression, and reduced use of high-risk medications during supervised tapering indicate potential benefits, although causal inferences cannot be drawn given the feasibility design. These findings provide practical insights to inform refinement and progression to larger controlled studies evaluating scalability and long-term effects in routine primary care.

Trial Registration: ClinicalTrials.gov NCT06361706; http://clinicaltrials.gov/ct2/show/NCT06361706 and NCT06964360; http://clinicaltrials.gov/ct2/show/NCT06964360

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KEYWORDS

augmented reality; chronic pain; deprescriptions; feasibility studies; patient-centered care; patient education as topic; primary health care; virtual reality

Introduction

Chronic pain is common and disabling, with a recent systematic review estimating prevalence across European adults at roughly 21%, though individual studies range from 12% to 48% depending on criteria used [1]. In Spain, nationwide surveys report similar levels, with around 1 in 4 adults affected, and higher rates among women and in the 55 - 75 age group [2]. Beyond prevalence, chronic pain is consistently linked with functional impairment, lower quality of life, and high health care use [1]. At a societal level, productivity losses from sick leave and early retirement have been estimated to consume up to 4% of GDP in some countries [3].

Primary care is where clinicians first diagnose, treat, and follow most people with chronic pain over time [4,5], heavily relying on pharmacological treatment. In this setting, providers frequently prescribe opioids, nonsteroidal anti-inflammatory drugs (NSAIDs), antidepressants, anticonvulsants, and benzodiazepines despite limited long-term benefit and safety concerns, particularly with opioid-benzodiazepine combinations [6,7]. Multidisciplinary group programs that combine physical, psychological, and self-management strategies may provide a safer and more comprehensive approach with effectiveness supported by evidence [8]. Yet, their accessibility remains inconsistent, constrained by structural and organizational barriers [9].

Extended reality (XR), including virtual reality (VR) and augmented reality (AR), is being explored as an addition to nonpharmacological pain strategies. Recent systematic reviews and early trials in specialist centers suggest XR interventions may help reduce pain intensity, support emotional regulation, and improve engagement [10-12]. A recent randomized trial reported that VR-based therapy improved clinical outcomes as well as brain imaging markers in chronic back pain [13]. Most of this evidence, however, comes from tightly controlled contexts rather than everyday practice, underscoring the need for feasibility and implementation studies in primary care and community settings [14,15].

We developed REDOCVR [RE (Reeducació), DOC (Dolor Crònic), VR (Virtual Reality)] in 2023 within a public primary care network in Catalonia, Spain, where multidisciplinary group programs for chronic pain were already established and delivered by psychologists and physiotherapists in line with the regional pathway [16]. Instead of developing a separate intervention or testing XR in a laboratory, we included it into existing sessions, keeping the same structure, timing, and professional roles. Clinicians and patients codesigned content, bringing together XR experiences for guided mindfulness, psychoeducation, distraction, and interactive motor exercises.

This paper examines the feasibility and implementation of REDOCVR in public primary care. By doing so, it directly addresses recent calls for research on how XR interventions can be integrated beyond specialist centers and sustained in routine clinical practice [14,15]. Its innovation lies in embedding XR into established multidisciplinary group programs, codesigned with patients and clinicians, rather than creating a new parallel service. This pragmatic approach ensured the program was conceived and delivered entirely within real-life clinical settings, focusing on implementation outcomes relevant for scalability.

Methods

Study Design and Setting

We conducted a hybrid type 2, nonrandomized, phased implementation study conducted in public primary care centers (PCC). The rollout was structured in three phases; this paper reports on Phases 1 and 2, which examined feasibility and optimization, while Phase 3 is ongoing and will be reported separately.

Phases of Implementation

Phase 1: Codesign and Single-Site Feasibility

The first phase combined the participatory development process with a pilot group at PCC Apenins-Montigalà. Between September 2023 and February 2024, a core team of a psychologist, a physiotherapist, family physicians, a medical XR developer, technical partners, and patient representatives worked together to define content, delivery conditions, and safety procedures.

Professionals and patients cocreated the content to reflect the priorities of primary care, and immersive content was iteratively refined to ensure usability and acceptability. This included recording 360° videos with audio guides, reusing mindfulness modules from a previous project [17] (body scan and mindful breathing), and adapting the self-compassion module for the context of chronic pain. In parallel, AR hand-tracking exercises were designed in collaboration with professionals and patients to support safe, engaging movement, aligned with the routine interventions of the original program.

The pilot group (February-March 2024) completed eight 90-minute weekly sessions, with immersive content adjusted to the therapeutic goals of each session. Feasibility work at this stage focused on usability, acceptability, satisfaction, and iterative refinements of both content and technical procedures. XR was initially integrated into all weekly sessions in Phases 1 and 2; later adjustments are reported in the *Discussion* section.

Phase 2: Multisite Optimization

The program was expanded to include 2 additional PCCs while continuing at Apenins-Montigalà, comprising a total of 7 groups (3 at the original center, 2 at each new site). From the second group onward in each center, a supervised medication tapering protocol was introduced by family physicians, with scheduled reviews aligned to study timepoints.

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Phase 3: Scale-Up

The program is currently extending to additional PCCs within Badalona Serveis Assistencials and to external institutions in the Catalan primary care system. This phase emphasizes readiness assessment, training of new professional teams, and preparation for replication beyond the initial network. The results from this phase will be reported separately.

Participants and Eligibility Criteria

Eligibility was limited to adults enrolled in chronic pain group programs routinely offered at the PCCs. Participants had experienced chronic pain for at least 3 months, most often related to fibromyalgia, with no restrictions on pain site or intensity. Exclusion criteria, based on diagnoses documented in the medical record, included severe psychiatric or cognitive disorders, epilepsy, major neurological or sensory impairments, contraindications for physical activity, or barriers that prevented regular attendance at group sessions.

Recruitment was coordinated by the physiotherapist and psychologist leading the groups at each center. Patients invited to join the chronic pain groups were informed that the program included the option of using XR as part of our research study. They could choose to participate with or without the XR component and were free to continue in the group even if they later decided to withdraw from the study. In routine practice, referrals to the chronic pain groups were generally based on patients presenting features such as central sensitization, emotional distress, kinesiophobia, or limited response to prior treatments, although these factors were not applied as formal inclusion criteria for the study. At a dedicated evaluation visit, eligibility was confirmed by the physiotherapist or psychologist responsible for the group, and written informed consent was obtained together with baseline data. All patients who were invited chose to participate.

As the intervention was embedded in standard care, no randomization or blinding was applied. No formal sample size calculation was conducted, as these phases focused on feasibility and to inform the design of subsequent groups. The sample size was pragmatic, determined by patient enrollment in chronic pain groups during the study period. A minimum of 30 participants was considered sufficient to capture feasibility issues and guide refinements for broader implementation.

Intervention

The intervention was delivered by psychologists, physiotherapists, and family physicians routinely leading group-based pain management programs. They received prior training and continuous technical support from the institutional innovation team, who had specific expertise in implementing XR in clinical care and codesigned the intervention content.

Immersive Dose and Delivery Conditions

XR content was applied for 15‑20 minutes per session, with duration adjusted to the therapeutic focus and participants' tolerance. All modules were delivered under direct facilitator supervision. Headsets (Meta Quest 2 and 3) were preloaded with the required content, sanitized between uses, and configured individually. Quest 3 devices were prioritized for AR passthrough sessions when available, given their superior visual quality.

To support acclimatization among first-time users, XR elements were introduced in a stepwise sequence. Early sessions began with a passive, audio-guided VR body scan, after which participants progressed to psychoeducational and mindfulness modules, and later to AR passthrough motor exercises and interactive tasks. This gradual progression reflected strategies already tested in other XR initiatives within our institution, where it proved effective in improving tolerability and reducing cybersickness [18].

Final Intervention Components

The codesign process resulted in 2 integrated components that became the stable structure of REDOCVR sessions (see Figures 1 and 2). The XR content targeted 4 core domains relevant to chronic pain care in primary care: mindfulness and attentional focus; cognitive reframing and self-compassion; distraction for symptom regulation; and exercises to encourage safe, engaging movement.

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Figure 1. Immersive content developed and implemented in REDOCVR Phase 1: Panels a–f illustrate the REDOCVR augmented reality (AR) application created for guided physiotherapy sessions, designed to encourage safe movement and reduce kinesiophobia. Tasks were implemented in passthrough mode with hand tracking: (a) basic target interaction, (b) activation of the user interface menu by facing the left palm toward the user, (c) manipulation of 3D objects to promote reaching and coordination, (d) mosquito interception game to train postural control and attentional focus, (e) spatial reasoning puzzle based on Tetris blocks, and (f) visual memory puzzle with image fragments. Panels g–i show Unity-based VR environments from the *Projecte Benestar* program, integrated into group psychology sessions to support nonpharmacological pain management: (g) body scan practice in a zen garden environment, (h) guided mindful breathing exercise at a virtual beach, and (i) psychoeducational module introducing the RAIN (Recognize, Allow, Investigate, Nurture) framework for emotion regulation.

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Figure 2. Implementation of XR content in REDOCVR sessions. The left column illustrates psychology-led sessions using the 360° virtual reality (VR) videos to support mindfulness and emotional awareness. A supervising tablet (top) allowed facilitators to monitor the video being displayed in the headsets, while group sessions (middle and bottom) were conducted with live guidance. The right column illustrates physiotherapy-led sessions. The top panel shows VR-based physical activity using controllers. The middle panel displays the augmented reality (AR) interface of the REDOCVR application with a gamified motor task from the participant's perspective. The bottom panel depicts AR passthrough exercises using hand tracking during group movement practice. All sessions were supervised to ensure patient comfort and safety.

1. Psychology-focused sessions used VR modules to support psychoeducation, mindfulness, and emotional regulation. Depending on the session, participants worked with either the created 360° videos with audio guides ("Making peace with the pain" on natural beaches and a mindful dive in the Barcelona Aquarium) or Unity-based VR environments illustrating psychoeducational and cognitive reframing concepts. Modules were brief, noninteractive, and activated by simple hand-tracking. Together, they provided complementary approaches to emotional regulation, designed to be accessible to first-time XR users and flexible across sessions.
2. Physiotherapy-focused sessions integrated XR tools to encourage physical activation and body awareness. The REDOCVR AR app projected virtual objects into the physical space using passthrough and hand tracking, with tasks chosen by the physiotherapist according to functional goals: target interactions (touching floating objects), intercepting exercises requiring postural control (reacting to moving stimuli at 2 difficulty levels), and motor puzzles (shape-matching tasks). These modules incorporated elements of gamification, embodiment, and immersive presence to encourage motivation, although these factors were not directly assessed as outcomes. To provide a structured comparison, some sessions also used VR movement games from Immersive Oasis (a Spanish XR start-up). These games, operated with headset controllers rather than hand tracking, promoted functional movement while allowing evaluation of engagement and tolerability across different formats (AR vs VR, hand tracking vs controllers). Implementation fidelity was maintained by the standardized session scheme and calendar already established for the chronic pain groups, into which XR modules were integrated uniformly across sites.

All immersive content was available offline, preloaded in the headsets. Apps did not collect or transmit data; the only element

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requiring Wi-Fi was the optional Reality Telling tablet app for synchronizing playback of 360° videos.

Outcome Measures

As this was an early-phase study, no explicit thresholds for feasibility or clinical outcomes were prespecified. The primary aim was to assess usability, tolerability, and feasibility of implementation under routine primary care conditions. The results were interpreted descriptively to guide adjustments in program delivery and inform the design of subsequent implementation phases, rather than to determine continuation or termination against predefined criteria.

Implementation Outcomes

Usability was assessed with 2 adaptations of the System Usability Scale (SUS), a validated instrument widely used in digital health research [19,20]. The patient version was reduced to 8 items, while the professional version retained the original 10 items with wording adapted to clinical use of XR. Both used 5-point Likert scales, with scores calculated following standard procedures and rescaled to a 0 - 100 range. This approach aligns with recommendations to adapt usability tools for real-world XR implementations [21] and is supported by evidence that removing alternating positive-negative phrasing improves clarity without compromising validity [22-24].

Satisfaction and engagement were evaluated with a 10-item questionnaire developed for this study, covering perceived usefulness, ease of use, content quality, emotional impact, and physical comfort, scored on a 5-point Likert scale with responses similarly rescaled to a 0 - 100 scale.

Adherence was defined as attendance at all scheduled sessions and completion of pre- or post-assessments. Most sessions were observed in person by the main investigator, with telephone debriefs where this was not possible. XR use and safety were monitored on a session-by-session basis, but without a structured or protocolized register; feedback was noted informally. Headset tolerability and safety were assessed with an 8-item questionnaire using 5-point Likert scales, covering comfort, fatigue, visual discomfort, dizziness, headache, and session interruption. Responses were analyzed descriptively at the item level rather than as a total score.

Qualitative feedback was obtained through a comments form, available at each session and again with the post-evaluation tests. The form contained a single free-text field without guiding questions. Responses were reviewed after each group to identify recurring perceptions. Informal remarks made during sessions were used to adjust delivery pragmatically but were not systematically examined.

Clinical Outcomes

Emotional well-being was measured with the 14-item Warwick-Edinburgh Mental Well-being Scale (WEMWBS), validated in Spanish samples with strong internal consistency (α=.90 - .93) [25,26].

Anxiety and depressive symptoms were assessed using the Hospital Anxiety and Depression Scale (HADS), Spanish version, which demonstrates strong internal consistency (α=.84 for anxiety, α=.85 for depression) and robust construct validity [27,28].

Central sensitization was evaluated with the Central Sensitization Inventory (CSI), scored 0 - 100, with scores ≥40 indicating clinically relevant sensitization. The Spanish version shows solid psychometric properties in clinical populations [29,30].

Health-related quality of life was measured with the 5-level EuroQol (EuroQol – 5 Dimensions – 5 Levels [EQ-5D-5L]), using Spanish population norms to derive utility indices [31,32].

Medication use was reviewed in scheduled visits with family physicians, who checked electronic prescriptions together with patients and confirmed actual doses and any additional drugs not recorded. This measure was applied only in groups that included the deprescribing component.

Data Management

Overview

We conducted assessments at baseline (month 0), post-intervention (month 2), and follow-up (month 5). Implementation outcomes were assessed at program completion, clinical outcomes at baseline and completion, and medication use at all 3 time points in groups where tapering was implemented. Questionnaires were administered on paper by the program facilitators, pseudonymized with unique alphanumeric codes, and transcribed into electronic spreadsheets. Data were stored on encrypted institutional servers with restricted access and regular backups, in compliance with Spanish data protection laws (Ley Orgánica de Protección de Datos y Garantía de Derechos Digitales 3/2018) and the European General Data Protection Regulation (EU 2016/679).

Statistical Analysis

Descriptive statistics were used to summarize sociodemographic data, clinical characteristics, and questionnaire responses. Continuous outcomes are presented as means with standard deviations or medians with interquartile ranges, according to distribution. Internal consistency was assessed for the adapted SUS questionnaires. Exploratory pre-post comparisons of clinical outcomes were conducted with paired-sample tests.

Reporting Guidelines

The study was reported in accordance with established guidelines. We followed the CONSORT extension for pilot and feasibility trials (see Checklist 1), the TIDieR checklist for intervention description (Checklist 2), RATE-XR for immersive technology research (Checklist 3), and iCHECK-DH for digital health implementation (Checklist 4).

Ethical Considerations

Ethical approval was obtained from the Institut Universitari d'Investigació en Atenció Primària Jordi Gol Research Ethics Committee for both study protocols (refs. 24/047-P and 24/211-ACps), which are registered at ClinicalTrials.gov (NCT06361706 and NCT06964360). The REDOCVR XR content was implemented only as nontherapeutic support within a group psychoeducational program. After review by the Spanish Agency of Medicines and Medical Devices, it was formally

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classified as nonmedical device software, and no regulatory authorization was required.

All participants provided written informed consent before enrollment. Study data were deidentified prior to analysis, and no personal or health identifiers were collected by the XR software. Participants did not receive compensation for their participation. Figure 2 includes images where participants and clinicians are partially identifiable; written informed consent for publication of these images was obtained from all individuals depicted and archived by the research team.

Results

Sample Characteristics and Adherence

A total of 42 participants were enrolled across 7 intervention groups at 3 PCCs during 2024. Of these, 36 (85.7%) participants completed the full intervention and both pre- and post-assessments, with no missing outcome data among completers. Analyses of clinical outcomes were based on this final sample (n=36), with a mean age of 57.7 years (SD=9.36; range 40 - 79) and a predominance of women (97.2%, n=35). Adherence was high, with the 6 dropouts attributed to patients' logistical or scheduling conflicts, with no study-related reasons reported. Figure 3 illustrates a CONSORT-style participant flow diagram, while Table 1 details group composition across phases, from initial optimization to the later inclusion of supervised medication tapering.

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Figure 3. Flow of participants through the REDOCVR intervention groups. CONSORT-style diagram illustrating enrollment, dropout, and analysis for the 7 nonrandomized groups implemented in 2024. A total of 42 participants were enrolled across 3 primary care centers, of whom 36 (85.7%) completed the full intervention and both pre- and post-assessments. Analyses of clinical outcomes were based on these 36 participants. Medication-related outcomes were analyzed separately in the subset of 22 participants who took part in groups that included supervised medication tapering.

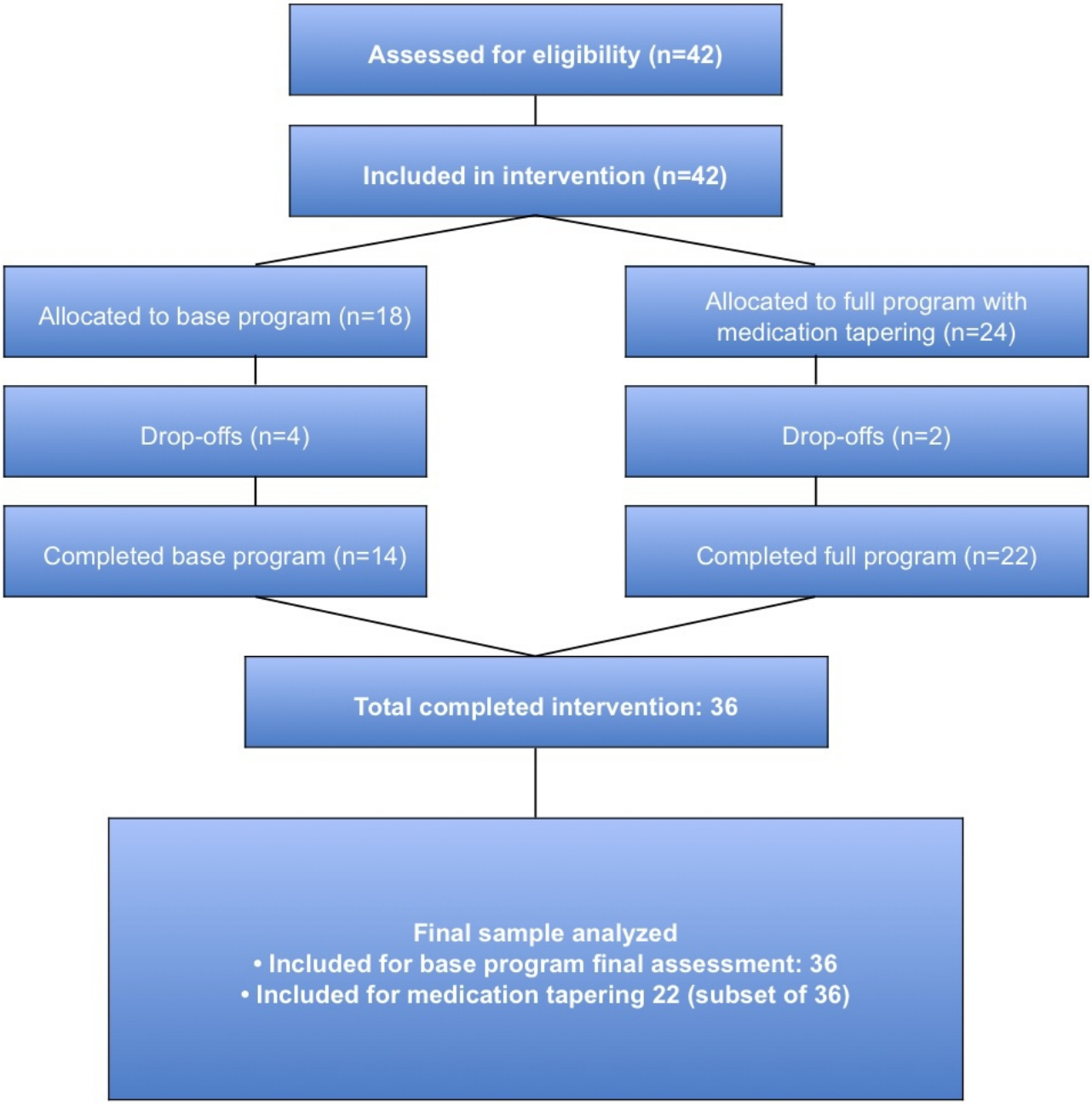

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Table . Distribution of REDOCVR intervention groups and participants completed in 2024[a].

PCC[b]	Group	Phase	Implementation	Program sessions	Included (N=42), n	Completed post-evaluation (N=36), n	Medication tapering (N=22), n
Apenins-Montigalà	Group 1	Phase 1	Base program optimization	Feb-Mar 2024	6	4	-
Apenins-Montigalà	Group 2	Phase 2	Introduction of medication tapering	May-Jun 2024	6	6	6
Apenins-Montigalà	Group 3	Phase 2	Fully optimized program	Sept-Oct 2024	6	5	5
Progrés-Raval	Group 1	Phase 2	Base program only	Apr-May 2024	6	5	-
Progrés-Raval	Group 2	Phase 2	Fully optimized program	Sept-Nov 2024	6	6	6
Morera-Pomar	Group 1	Phase 2	Base program only	Apr-Jun 2024	6	5	-
Morera-Pomar	Group 2	Phase 2	Fully optimized program	Sept-Nov 2024	6	5	5

[a]Distribution of REDOCVR intervention groups completed in 2024 across 3 public primary care centers (PCCs) in Catalonia, Spain. The study followed a hybrid type 2, nonrandomized, phased implementation design. This paper reports on Phases 1 and 2, which focused on feasibility and optimization, while Phase 3 is ongoing and will be reported separately. The table shows participants' details by implementation phase, session completion, and inclusion of supervised medication tapering where applicable.

[b]PCC: primary care center.

Implementation Outcomes

System Usability

Patient-reported usability was high, with a mean SUS score of 81.4 (SD 17.1; 95% CI 75.6 - 87.1). Most participants (83%, n=30) scored above the standard benchmark of 68, indicating strong perceived usability. Item-level results, including English translations of the adapted questionnaire items, are provided in Table 2. Internal consistency of the adapted 8-item scale was acceptable (Cronbach α=.70).

SUS scores from 8 health care professionals (3 psychologists, 3 physiotherapists, 1 family physician, and 1 biomedical technician) averaged 59.06 (SD 8.96; 95% CI 51.6 - 66.5). Item-level ratings showed a mixed picture, with perceived contribution to patient care and clarity of simulation features scoring high, while system integration and need for support were rated lower. Internal consistency was low (Cronbach α=.28).

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Table . Usability and satisfaction outcomes: patient and professional System Usability Scale (SUS), and patient satisfaction questionnaire.

Questions (English translation)	Mean (SD)	95% CI
(A) Patients—Adapted SUS (n=36, 8 items; Cronbach α=.70)[a]		
I think I would like to use this program frequently.	90.28 (22.58)	82.64 - 97.92
I think the program is unnecessarily complex.	75.69 (34.06)	64.17 - 87.22
I think the exercises are more engaging with the VR[b] headset than conventional methods.	82.64 (32.08)	71.78 - 93.49
I think the simulation options are clear and well integrated.	93.75 (19.25)	87.24 - 100.26
I think some options are difficult to follow.	75.69 (34.58)	63.99 - 87.4
I think people will learn to use this system easily.	81.25 (29.5)	71.27 - 91.23
I felt comfortable using this system.	89.58 (21.86)	82.19 - 96.98
I had to learn many things before being able to use the system.	61.81 (40.31)	48.17 - 75.44
Total patients SUS score	81.35 (17.1)	75.56 - 87.14
(B) Professionals—Adapted SUS (n=8, 10 items; Cronbach α=.28)[c].		
I believe this program will help improve the quality of patient care.	84.38 (12.94)	73.56 - 95.19
I believe the program interface is intuitive for the user.	75 (18.9)	59.2 - 90.8
I believe the program can be easily integrated into daily clinical practice.	53.13 (36.44)	22.66 - 83.59
I believe the simulation's features are clear and relevant to patient care.	81.25 (11.57)	71.57 - 90.93
Some features of this system may be difficult for patients to understand or use.	28.13 (20.86)	10.68 - 45.57
I believe patients will be able to learn to use this system easily.	68.75 (22.16)	50.22 - 87.28
I felt comfortable using this system for patient care.	78.13 (20.86)	60.68 - 95.57
You needed additional time to learn how to use this system correctly.	40.63 (32.56)	13.4 - 67.85
I believe the weight and design of the headset may be uncomfortable for some patients.	56.25 (34.72)	27.22 - 85.28
I believe using the headset and controllers could be difficult for some patients.	25 (18.9)	9.2 - 40.8
Total professionals SUS score	59.06 (8.96)	51.57 - 66.55
(C) Patients—Satisfaction questionnaire (ad hoc, n=36, 10 items; Cronbach α=.81)[d].		
Overall, how do you rate the VR experience during the chronic pain management sessions?	88.89 (13.94)	84.17 - 93.61
What is your opinion on the usefulness of VR for pain reduction?	82.64 (15.61)	77.36 - 87.92
Is the visual and image quality of the VR satisfactory for you?	88.19 (12.66)	83.91 - 92.48
Is interaction with the VR during sessions easy to understand and use?	87.5 (17.42)	81.6 - 93.4
How do you rate physical comfort while using VR?	80.56 (21.64)	73.23 - 87.88

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Questions (English translation)	Mean (SD)	95% CI
Has VR improved your concentration and ability to manage pain?	73.61 (21.5)	66.34 - 80.89
What do you think about the variety of VR content available for your pain management sessions?	82.64 (18.73)	76.3 - 88.98
How do you rate the support and guidance you received during the VR sessions?	92.36 (14.42)	87.48 - 97.24
Is the duration of the VR sessions adequate for your goals?	75 (26.05)	66.19 - 83.81
Do you intend to continue using VR in your pain management sessions?	72.92 (25.62)	64.25 - 81.58
Totalpatients's satisfaction score	82.43 (11.69)	78.48 - 86.39

[a]Patient System Usability Scale (SUS, adapted 8-item version; n=36). Total and item-level mean scores are presented on a 0–100 scale.

[b]VR: virtual reality.

[c]Professional SUS (standard 10-item version; n=8 health care professionals: 3 psychologists, 3 physiotherapists, 1 family physician, and 1 biomedical technician). Total and item-level mean scores are presented on a 0–100 scale.

[d]Patient satisfaction questionnaire (ad hoc; n=36). Items were rated on a 0–100 scale and are shown as mean (SD). All questionnaire items were translated into English for reporting.

Satisfaction

Overall satisfaction was high, with a mean score of 82.4 (SD 11.7; 95% CI 78.4 - 86.4). The highest ratings were for support and guidance received (92.4), overall experience (88.9), and visual quality (88.2). Lower, though still positive, scores were reported for intention to continue use (72.9), session duration (75), and concentration and pain management (73.6). Item-level results with English translations are presented in Table 2.

Tolerability and Safety

Headset tolerability was generally high, with most participants disagreeing with statements indicating discomfort or adverse effects (Table 3). Dizziness (5.6%) and headache (5.6%) were rarely reported as frequent, and only 1 participant (2.8%) stopped a session due to discomfort. Fatigue in arms or hands was more common (33.3% agreement), likely reflecting the physical effort of interactive tasks rather than adverse effects. About half (50%) of participants rated the headset as comfortable for prolonged use. Overall, these findings suggest good tolerability with only occasional transient discomfort. Supervision confirmed correct use of XR without major incidents, and the open-ended feedback gathered during these sessions is described in the following section.

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Table . Tolerability and safety of VR headsets (n=36)[a].

Question (English translation)	Strongly disagree (%)	Disagree (%)	Neutral (%)	Agree (%)	Strongly agree (%)
The headset was very heavy and uncomfortable	50	8.3	8.3	25	8.3
Using the headset and controls was very complicated	61.1	13.9	8.3	11.1	5.6
I felt fatigue in my arms and fingers	44.4	13.9	8.3	25	8.3
I felt visual discomfort	72.2	11.1	2.8	11.1	2.8
I felt dizzy	63.9	22.2	8.3	2.8	2.8
I experienced headache	77.8	8.3	8.3	2.8	2.8
I had to stop the simulation due to discomfort	83.3	8.3	5.6	0	2.8
I think it would be comfortable to use these glasses for a long time	8.3	13.9	27.8	22.2	27.8

[a]Tolerability and safety of virtual reality (VR) headsets during REDOCVR sessions among patients with chronic pain in public primary care (n=36). Responses are reported as the percentage of participants selecting each option on a 5-point Likert scale (strongly disagree to strongly agree). Questionnaire items were translated into English for reporting.

Qualitative and Comparative Feedback

Patient feedback, collected through the comments form (see Multimedia Appendix 1 for thematic analysis), underscored both therapeutic and practical aspects of the program. The 360° mindfulness videos and the self-compassion module were consistently described as the most meaningful. Many participants noted that the immersive format of body scan and breathing practices made these techniques easier to follow, while psychologists emphasized in their debriefings that these elements were particularly useful for consolidating skills introduced in other sessions. A few participants reported brief emotional discomfort during emotion-focused modules; these reactions were anticipated as part of the process, addressed by clinicians, and did not disrupt participation.

Patients also drew clear contrasts between modalities. AR exercises were described as intuitive and less tiring, with passthrough providing orientation that supported group flow. VR was seen as more immersive and distracting, though some participants reported temporary dizziness, fatigue, or visual strain after longer interactions. Across groups, patients consistently preferred hand-tracking over controllers, citing its natural interaction and shorter setup time (see Multimedia Appendix 2 for a video of the program sessions and content).

Professionals echoed some of these observations and noted additional logistical challenges. VR sessions required extra time to configure safety areas and adjust headsets individually. At least 1 physiotherapist described difficulty leading a group of 8 patients by himself, as sequential headset setup left participants waiting; these issues were less frequent when 2 or 3 professionals co-led with technical support. Setting up the connection for tablet-controlled synchronization of 360° videos was also seen as an added burden, further highlighting the need for streamlined logistics (see Multimedia Appendix 2 for a video of the program sessions and content).

Across groups, patients suggested extending the program, increasing session frequency, and considering access to VR content outside the clinical setting.

Clinical Outcomes

Normality assumptions determined the choice of test: paired-sample *t* tests were applied to normally distributed continuous outcomes (WEMWBS, HADS, CSI; Table 4), while Wilcoxon signed-rank tests were used for ordinal EQ-5D-5L domains (Table 5).

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Table . Paired-sample *t* tests for normally distributed outcomes.

Variable	Mean difference (95% CI)	*P* value	Cohen *d*
Emotional wellbeing	4.83 (2.92 to 6.74)	<.001	0.86
HADS-Anxiety[a]	–2.47 (–3.75 to –1.20)	<.001	0.66
HADS-Depression	–1.64 (–2.53 to –0.75)	<.001	0.62
CSI[b]	–3.22 (–7.18 to 0.73)	0.1107	0.28

[a]HADS: Hospital Anxiety and Depression Scale.
[b]CSI: Central Sensitization Inventory.

Table . Wilcoxon signed-rank test results for EQ-5D-5L[a] dimensions

EuroQol (EQ-5D-5L) dimensions	HL[b] median change (95% CI)	*P* value	Effect size (r)	Interpretation
Mobility	–1.0 (–1.0 to 0.0)	0.0182	0.39	Significant improvement (moderate)
Self-care	0.0 (–0.5 to 0.0)	0.3374	0.16	No significant change (small)
Usual activities	0.0 (–0.5 to 0.5)	0.772	0.05	No change (very small)
Pain/Discomfort	–0.5 (–0.5 to 0.0)	0.084	0.29	Trend toward improvement (moderate)
Anxiety/Depression	0.0 (–0.5 to 0.0)	0.2869	0.18	No significant change (small)

[a]EQ-5D-5L: EuroQol 5-Dimension 5-Level questionnaire.
[b]HL: Hodges-Lehmann.

Table 6 presents pre-post values for clinical outcomes (n=36). Emotional well-being (WEMWBS) increased from 16.9 (SD 4.9) to 21.7 (SD 6.1), with a mean change of 4.8 (95% CI 2.9 - 6.7, *P*<.001, Cohen *d*=0.86). Anxiety symptoms (HADS-Anxiety) decreased from 13.1 (SD 4.3) to 10.7 (SD 4.3), mean change –2.5 (95% CI –3.8 to –1.2, *P*<.001, Cohen *d*=0.66), and depressive symptoms (HADS-Depression) from 10.6 (SD 3.4) to 9 (SD 4.2), mean change –1.6 (95% CI –2.5 to –0.7, *P*<.001, Cohen *d*=0.62). Central sensitization (CSI) declined slightly, from 60.7 (SD 14.2) to 57.5 (SD 13.4), mean change –3.2 (95% CI –7.2 to 0.7, *P*=.11, Cohen *d*=0.28).

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Table . Clinical outcomes: descriptive statistics and pre–post differences (n=36)[a].

Variable	Mean (SD)	Median (IQR)	Range (Min-Max)	95% CI for mean
Descriptive statistics[b]				
Emotional wellbeing (Pre)	16.89 (4.92)	16.5 (6.25)	8 - 26	15.22 - 18.55
Emotional wellbeing (Post)	21.72 (6.14)	23.0 (8.25)	7 - 34	19.64 - 23.80
HADS-Anxiety (Pre)	13.14 (4.28)	13.5 (5.5)	4 - 20	11.69 - 14.59
HADS-Anxiety (Post)	10.67 (4.27)	10.5 (7.25)	4 - 20	9.22 - 12.11
HADS-Depression (Pre)	10.61 (3.43)	10.0 (5.0)	2 - 18	9.45 - 11.77
HADS-Depression (Post)	8.97 (4.23)	9.0 (5.0)	1 - 21	7.54 - 10.40
CSI[c] (Pre)	60.72 (14.18)	60.0 (18.0)	34 - 95	55.93 - 65.52
CSI (Post)	57.50 (13.42)	58.0 (15.25)	33 - 94	52.96 - 62.04
Mobility (Pre)	2.19 (0.92)	2.0 (1.25)	1 - 4	1.88 - 2.51
Mobility (Post)	1.78 (0.83)	2.0 (1.0)	1 - 4	1.50 - 2.06
Self-Care (Pre)	1.72 (0.66)	2.0 (1.0)	1 - 3	1.50 - 1.95
Self-Care (Post)	1.58 (0.81)	1.0 (1.0)	1 - 4	1.31 - 1.86
Usual activities (Pre)	2.47 (1.00)	2.5 (1.0)	1 - 5	2.13 - 2.81
Usual activities (Post)	2.42 (1.20)	3.0 (2.0)	1 - 5	2.01 - 2.82
Pain/Discomfort (Pre)	3.69 (0.75)	4.0 (1.0)	2 - 5	3.44 - 3.95
Pain/Discomfort (Post)	3.44 (0.73)	4.0 (1.0)	2 - 5	3.20 - 3.69
Anxiety/Depression (Pre)	3.31 (1.14)	3.0 (1.0)	1 - 5	2.92 - 3.69
Anxiety/Depression (Post)	3.06 (1.33)	3.0 (2.0)	1 - 5	2.61 - 3.51

[a]Clinical outcomes for patients with chronic pain participating in the REDOCVR program in public primary care (n=36).

[b]Descriptive statistics for all outcome measures, including mean (SD), median (IQR), range, and 95% CI.

[c]CSI, Central Sensitization Inventory.

For quality of life (EQ-5D-5L), Mobility improved significantly (median change –1.0, 95% CI –1.0 to 0.0, P=.02, r=0.39), while Pain/Discomfort showed a nonsignificant trend toward improvement (median change –0.5, 95% CI –0.5 to 0.0, P=.08, r=0.29). Self-Care, Usual Activities, and Anxiety/Depression domains showed no significant changes.

Medication Tapering

Among the 22 participants who followed the deprescription protocol, medication use declined across several categories (Table 7). Between baseline and the 5-month review, the largest mean reductions were in benzodiazepines (71.7%, 6 complete discontinuations), opioids (41.8%, 5 discontinuations), and muscle relaxants (48%). More modest decreases were seen for NSAIDs and non-opioid analgesics. Patterns for antidepressants and pain modulators were mixed, with some patients starting new treatments during follow-up.

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Table . Medication tapering by therapeutic category at 2 and 5 months post-intervention[a].

Medication type	Timepoint (months)	Mean (%)	Median (%)	IQR (%)	Range (%)	N complete stops
NSAIDs[b]	2	29.86	33	45.75	0-100	1
NSAIDs	5	25.14	16.5	50	–100 to 100	2
Non-opioid analgesics	2	28.31	12.5	37.25	0-100	2
Non-opioid analgesics	5	30	12.5	49	0-100	2
Antidepressants	2	1.61	0	0	–100 to 100	3
Antidepressants	5	8.29	0	0	–100 to 100	6
Benzodiazepines	2	45	25	100	0-100	4
Benzodiazepines	5	71.7	100	45.75	0-100	6
Pain modulators	2	19.44	0	25	0-100	1
Pain modulators	5	34.22	25	50	0-100	2
Opioids	2	40.13	33	60	–100 to 100	5
Opioids	5	41.8	43	93	–100 to 100	5
Muscle relaxants	2	48	48	23	25-71	0
Muscle relaxants	5	48	48	23	25-71	0
Others	2	25	25	0	25-25	0
Others	5	100	100	0	100-100	1

[a]Medication tapering by therapeutic category at 2 and 5 months after participation in the REDOCVR program (n=22 patients with medication follow-up). Values represent percentage change in daily intake from baseline to each follow-up. Changes were calculated for each medication record and then aggregated by category. “N complete stops” indicates the number of participants who fully discontinued that medication. Negative values (eg, –100%) denote initiation of a medication not used at baseline. Data are reported as mean, median, interquartile range (IQR), and minimum-maximum percentage change for each category. “Others” refers to a single case of Versatis (lidocaine medicated plaster).

[b]NSAIDs: nonsteroidal anti-inflammatory drugs.

Discussion

Principal Findings

This study examined the early implementation of REDOCVR, an XR-enhanced group program for chronic pain in primary care. The findings suggest that immersive technologies can be integrated into existing care structures without disturbing routine delivery.

Satisfaction, tolerability, and usability indicators provide additional insight into how the program was received. Patients rated the sessions positively, reporting high satisfaction and minimal discomfort. Cybersickness was rare, and overall headset tolerance further supported the acceptability of XR in this population. The adapted 8-item SUS for patients reduced response burden while maintaining validity, consistent with prior analyses of SUS modifications [21-24,33]. In contrast, professional SUS scores showed low internal consistency, likely due to the small and heterogeneous sample. Such factors are known to reduce the stability of Cronbach α [34,35], whereas prior studies suggest that 10-item adaptations generally retain reliability [21,22]. Our findings, therefore, probably reflect contextual heterogeneity rather than flaws in the instrument itself.

An exploratory review of the open comments provided complementary insights into participants’ and professionals’ experiences with XR. Feedback suggests that XR was experienced less as a novel intervention in itself and more as a support that appeared to enhance engagement with the program’s therapeutic content. In psychology-led sessions, immersive tools supported mindfulness and self-compassion practices that some patients otherwise found difficult to understand. In physiotherapy-led sessions, AR passthrough helped participants perform movements in a safe and supervised way, while VR increased immersion and motivation, both encouraging patients to attempt physical activities they would normally avoid.

Exploratory clinical findings suggested improvements in emotional well-being, anxiety, and depression, with effect sizes in the moderate-to-large range. Statistically significant improvements were observed in Mobility on the EQ-5D-5L, while Pain/Discomfort showed only a nonsignificant positive trend. Among participants enrolled in the deprescription protocol, benzodiazepine, opioid, and NSAID intake decreased, and several participants achieved complete discontinuation. Although causality cannot be inferred, these results are consistent with the possibility that group-based interventions may complement structured deprescription strategies [36].

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Comparison With Prior Work

While our findings on patient usability and clinical outcomes align with the existing literature [10,37], the primary contribution of this study is its focus on pragmatic implementation within a public primary care setting. We have encountered barriers in early adoption similar to other reports related to technical setup and workflow adjustments [38]. Prior reviews have noted that most VR interventions for pain concentrate on supporting specific aspects of health literacy or self-management rather than integration into routine care [39]. By embedding XR within an established group program rather than running it in parallel, REDOCVR addresses adoption challenges noted in recent reviews [14,15,40] and shows how immersive tools can fit into everyday service delivery. Delivering XR in group sessions brings clear advantages, including peer support, efficiency, and easier integration into existing care pathways, though it comes at the expense of individualized tailoring. Meta-analytic evidence in chronic pain indicates that group-based approaches can achieve outcomes comparable to individual formats [41]. This appears particularly relevant in the context of the public health care system, where resource optimization is not only desirable but often decisive for adoption.

The improvements in emotional well-being and functional outcomes align with the psychoeducational and behavioral mechanisms targeted, consistent with results from mindfulness- and acceptance-based approaches [8,13]. The reduction in medication use also mirrors outcomes from other multidisciplinary primary care interventions that combine patient education with supervised tapering [5]. What our findings add is preliminary evidence that such effects may be achievable when immersive tools are embedded into routine group care, rather than tested only in parallel or experimental conditions.

Limitations

The intervention was delivered to a modest number of groups within a supportive institutional setting, which may limit direct transferability to other contexts. Resources such as trained staff, headset availability, and organizational readiness facilitated implementation and should be considered when adapting the model elsewhere. Data collection on implementation fidelity was pragmatic. For instance, the dose of immersive exposure was guided by a time range (15 - 20 min) and adjusted for tolerance, but not strictly logged for each individual patient in every session. Adherence was assessed through attendance records, while adverse effects were monitored through informal therapist feedback and a single post-intervention questionnaire, rather than a structured, session-by-session register. The qualitative component was restricted to an exploratory review of written comments. While this offered useful contextual insights for program refinement, it was not intended as a formal qualitative study.

Other limitations are typical of early-phase implementation research, and exploratory clinical outcomes should be interpreted with caution. The absence of randomization and a control group limits causal inference. Generalizability is constrained by the modest and predominantly female sample (97%), which reflects the higher prevalence of chronic pain among women and the predominance of female participation in primary care group interventions in Spain [2,42]. This imbalance may restrict the applicability of findings to male patients. Participants also represented a heterogeneous chronic pain population, and we did not stratify by phenotype (nociceptive, neuropathic, or nociplastic), which may have masked differential responses. The group delivery model, while resource-efficient and well-suited to public primary care, inevitably restricts opportunities for individual tailoring [40]. The use of self-reported measures introduces potential recall and social desirability bias. Positive findings may have been partly influenced by a novelty effect. Finally, the 5-month follow-up is insufficient to establish the durability of changes over time.

Implications and Future Directions

Despite these constraints, the findings have already informed practical adjustments. Feedback from patients and professionals in Phases 1 and 2 reinforced the institutional support. Patients reported high satisfaction and usability, while professionals highlighted integration and workflow challenges. Combined with the clinical findings, these insights guided the Phase 3 refinements. The program was refined in collaboration with the full clinical team, leading to optimizations to improve feasibility.

In physiotherapy sessions, AR proved more suitable for larger groups, where supervision and interaction needed to be fluid, while VR was reserved for smaller groups. Both patients and professionals clearly favored hand-tracking, and all VR content was adapted accordingly, eliminating the need for controllers in the VR exercise games. Synchronizing 360° videos from the tablet required stable Wi-Fi, which was not always available. External routers were used to compensate, adding setup complexity. Efforts are underway to improve connectivity in PCCs and reduce facilitator workload.

Informed by early-phase findings and aligned with Catalan health system guidelines, the program will now follow the conventional format of 12 weekly sessions co-led by a psychologist and a physiotherapist, with selected sessions involving family physicians and nutritionists to reinforce healthy habits. XR use has been reorganized to fit within this structure, concentrated into 4 sessions—2 psychology-led (mindfulness and self-compassion) and 2 physiotherapy-led (motor activation). This targeted approach preserves therapeutic value while optimizing headset use and technical support across centers.

Future evaluation should focus on systematic data collection related to implementation fidelity. With XR use now organized into defined modules, session-by-session monitoring will allow more precise analysis of exposure, usability, and adverse effects across different modalities (eg, VR vs AR, passive vs interactive content). The expansion to additional centers and teams will be accompanied by structured pre-implementation focus groups and complementary usability strategies. Combined with established implementation frameworks, these steps are expected to generate the structured evidence needed to support broader adoption. By linking fidelity monitoring with pragmatic implementation, REDOCVR may help close the gap between immersive research and everyday chronic pain care.

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Conclusions

The first 2 phases of REDOCVR suggest that a person-centered, codesigned XR program can be incorporated in primary care chronic pain groups under real-world conditions. The intervention showed high adherence and favorable usability, and both patients and professionals valued its contribution to engagement and session delivery. Exploratory improvements in emotional well-being and reductions in high-risk medication use with supervised tapering are promising but should be interpreted with caution given the feasibility design.

This study is, to our knowledge, the first to develop and evaluate an XR program entirely within primary public health care. The findings offer practical guidance for refining XR-based interventions and preparing for wider scale-up. Ongoing work on Phase 3 across additional centers will further clarify long-term outcomes, scalability, and adaptability to different settings.

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Data Availability

The anonymized datasets generated and analyzed during this study are available from the corresponding author upon reasonable request and subject to approval by the Ethics Committee.

Authors' Contributions

Conceptualization: AFB, CTC, JFC, NMB
Data curation: JFC
Formal analysis: JFC
Investigation: AFB, CTC, EVL, JFC, LVU, MRB, PSB
Methodology and validation: AFB, CTC, JFC, NMB
Project administration: JFC
Resources: JFC
Software and VR content development: JFC
Writing–original draft preparation: JFC
Writing–review and editing: AFB, CTC, EVL, JFC, LVU, NMB

Conflicts of Interest

None declared.

Multimedia Appendix 1
Thematic analysis of patient feedback with illustrative quotes.
[PDF File, 77 KB - xr_v2i1e82858_app1.pdf]

Multimedia Appendix 2
REDOCVR BSA overview 2025: project content sample and real-life use in primary care.
[MP4 File, 123500 KB - xr_v2i1e82858_app2.mp4]

Checklist 1
CONSORT Checklist (Feasibility Extension).
[PDF File, 64 KB - xr_v2i1e82858_app3.pdf]

Checklist 2
TIDieR Checklist.
[PDF File, 61 KB - xr_v2i1e82858_app4.pdf]

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Checklist 3
RATE-XR Checklist.
[PDF File, 66 KB - xr_v2i1e82858_app5.pdf]

Checklist 4
iCHECK-DH Checklist.
[PDF File, 63 KB - xr_v2i1e82858_app6.pdf]

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Abbreviations

AR: augmented reality
CSI: Central Sensitization Inventory
EQ-5D-5L: EuroQol – 5 Dimensions – 5 Levels
HADS: Hospital Anxiety and Depression Scale
NSAIDs: nonsteroidal anti-inflammatory drugs
PCC: primary care center
REDOCVR: RE (Reeducació), DOC (Dolor Crònic), VR (Virtual Reality)
SUS: System Usability Scale
VR: virtual reality
WEMWBS: Warwick-Edinburgh Mental Well-being Scale
XR: extended reality

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Association Between Sensation Seeking and Fear Response: Interventional Study of Personality and Behavior Using a Virtual Reality Heights Simulation

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Abstract

Background: Immersive virtual reality (VR) technology presents digital simulations that create the sense of an actual experience. VR simulations are persuasive enough to elicit physiological reactions that mirror real-world responses. Prior research suggests that fear responses and sensation seeking are inversely correlated, but that work largely relies on self-reported outcomes and hypothetical scenarios.

Objective: To more closely model real-world phenomena, we tested for inverse associations using an experiential height exposure simulation and a behavioral task for sensation seeking. We tested these associations comprehensively by using multiple methods for convergent evidence.

Methods: A total of 57 healthy undergraduates participated in an interventional study that included an anxiety-inducing VR simulation, behavioral tasks, and personality inventories. The VR paradigm (Richie's Plank) prompted users to walk across and step off a plank at the top of a skyscraper. This simulation of extreme height exposure and falling was intended to evoke fear. Physiological recordings and self-reported state anxiety were collected prior to and during the experience. Behavioral sensation seeking was quantified using an olfactory choice task offering a "boring" or "exciting" (risky) option varying in intensity and pleasantness. Evoked fear was calculated as the difference between the calm (pre-plank) and provoked fear state (standing on the plank), with correlations performed between evoked fear and personality and behavioral measures. The false discovery rate was set to $q<.05$, with analyses conducted in SPSS.

Results: The VR experience evoked self-reported fear ($P<.001$) and physiological arousal ($P<.006$ for heart rate and $P<.017$ for respiration). Acrophobia correlated with self-reported fear in men and women ($P<.01$). Behavioral sensation seeking negatively correlated with both self-reported fear ($P=.02$) and increased heart rate in men ($P=.02$). Behavioral and self-reported sensation seeking were uncorrelated ($P=.89$). Self-reported fear was uncorrelated with physiological fear responses ($P>.46$).

Conclusions: VR simulations can produce lifelike responses to scenarios that are impractical to test in reality. Our demonstration of an experiential manipulation negatively correlating with sensation seeking behavior in men increases confidence in other findings from studies using more traditional methods. Our use of VR along with objective measures, for example, behavioral tasks, and subjective measures, for example, self-report, confirm the effectiveness of these tools to investigate behavioral health topics. Our findings further suggest that sex is an important intervening factor for fear and sensation seeking and that additional study is warranted. This study highlights the potential of VR to expand convergent validity more broadly with other traits and paradigms. Finally, VR technology permits presenting highly abstract or improbable scenarios, thus expanding the range of topics for behavioral investigations. Given the ever-wider adoption of immersive therapeutics in the clinic, VR research will continue to facilitate the study of biobehavioral outcomes and interactions with personality factors and advance actionable knowledge for clinical applications.

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KEYWORDS

behavioral psychology; immersion; immersive virtual reality; novelty seeking; real-life responses; phobia; risk-taking; simulation

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Introduction

Immersive virtual reality (VR) produces the functional and behavioral equivalence of actually being in a place, known as "presence" [1-5]. Immersion arises from high-fidelity stereoscopic visual and 3D audio stimuli that respond to user inputs; together, these create an "inclusive, extensive, surrounding, and vivid illusion of reality" [6]. Germane to clinical research, VR can deliver experiences that feel authentic but would otherwise be too dangerous, costly, or impractical to administer in a laboratory setting [1]. Until recently, research on evoked fear responses generally relied on affective pictures, video, and threat scenarios [7-9]. Extending prior research demonstrating that increasing immersive properties increased evoked responses [10,11], VR technology offers the promise of delivering experiences that are interactive, vivid, powerful, customizable, and standardized for studying clinically relevant outcomes.

Fear is an arousal response to threat stimuli, whereas anxiety occurs while approaching or anticipating a threat [12]; however, the distinction between fear and anxiety becomes blurred as the threat gets closer or more certain [13]. Unreasonable fear and anxiety elicited by particular stimuli can manifest as specific phobias, which occur in ~10% of the population and are highly comorbid, especially with anxiety, mood, and personality disorders [14]. The fear of heights is the second most common among these specific fears, with a prevalence of 4.5% [14], and is twice as common in women than in men [14,15]. The physiological fear response is mediated by the Fight/Flight/Freezing System and autonomic arousal, which can be readily quantified using altered heart rate [12,16]. Longitudinal evidence suggests that evoked physiological responses are more reliable than baseline physiological measures [17]. Further, physiological responses appeared to be more sensitive than self-reported valence to simulated threats when those threats were more lifelike and created by computer-generated graphics [11]. Immersive VR compared to 2D versions of provocative scenes evoked stronger physiological and emotional responses, coinciding with a stronger sense of presence [10,18]. Prior work indicates that virtual height simulations effectively elicit fear-related arousal [5,19]. We reasoned that a realistic experiential fear provocation would be highly appropriate for investigating associations with other objectively measured behavioral outcomes.

Sensation seeking, defined as "the seeking of varied, novel, complex, and intense sensations and experiences, and the willingness to take physical, social, legal, and financial risks for the sake of such experience" [20], is a putative stress buffer [21]. It is negatively associated with anxiety [19,22,23], risk perception [22,24], and fear responses [25]; however, the associations differ by sex (particularly on the Experience Seeking dimension) [26]. Unsurprisingly, fear-inducing activities (eg, hang-gliding, BASE jumping) attract high sensation seekers [27,28]. Moreover, many "extreme sports" (eg, bungee jumping, skydiving, ultralight piloting) evoke the fear of falling, a powerful and common "natural fear" in humans [29].

Sensation seeking is traditionally measured with self-report inventories [30,31]. To quantify sensation seeking and overcome some of self-report's intrinsic limitations, such as social desirability, self-awareness, cultural limitations, and criterion contamination [32-35], we created a behavioral task that models the key aspects of this trait [36]. The Aroma Choice Task (ACT) quantifies sensation seeking behavior as a binary choice between olfactory stimuli varying in intensity, novelty, and riskiness using actual sensory experiences presented in real time. Sensation-seeking behavior in this task correlates with self-reported sensation seeking [36], reward-related brain activation [37], and alcohol-induced shifts in reward preference [38]. Given the body of work suggesting that studies relying on low-realism tasks, hypothetical choices, and self-report questionnaires limit neurobehavioral [39] and behavioral genetic [40] conclusions, our objective sensation seeking task quantifies the behavioral trait as described by Zuckerman [30].

While virtual height simulations consistently elicit physiological reactions [5,19,41,42], only a few studies have examined relationships between behavior and sensation seeking; however, in VR [19,43], no studies, to the best of our knowledge, have tested for associations of physiological fear responses and behavioral sensation seeking. We expect more ecologically valid manipulations (ie, greater resemblance to real-world experience) of fear and anxiety, such as a realistic VR simulation of extreme heights, paired with objective behavioral measures of sensation seeking to reveal more generalizable findings for clinical research. Here, we elicit fear responses with an immersive interactive height exposure simulation [44] and test for associations with sensation seeking behavior. We quantify fear responses as subjective (evoked state anxiety) and objective (evoked physiological arousal). We hypothesize that (1) the virtual height simulation will increase evoked state anxiety and physiological arousal, (2) evoked state anxiety and physiological fear responses will be positively associated, (3) height anxiety will correlate with evoked state anxiety, (4) behavioral sensation seeking and self-reported evoked state anxiety will be negatively associated, and (5) behavioral sensation seeking and physiological fear response will be negatively associated. We also explore potential correlations between behavioral and self-reported sensation seeking.

Methods

Ethical Considerations

The Indiana University Institutional Review Board approved all recruiting and study procedures (protocol number 17398). Students provided informed consent before study participation. Privacy and confidentiality were maintained for all participants, and compensation was awarded in the form of class credit.

Participants

A total of 57 healthy undergraduate students were recruited from an urban midwestern university via online listings through the university's Sona Systems human subjects pool; course credit was provided for participation. Students provided informed consent before study participation. Exclusions included poor sense of smell, extreme sensitivity to odors or volatile chemicals, chronic or current asthma, pregnancy or nursing, or

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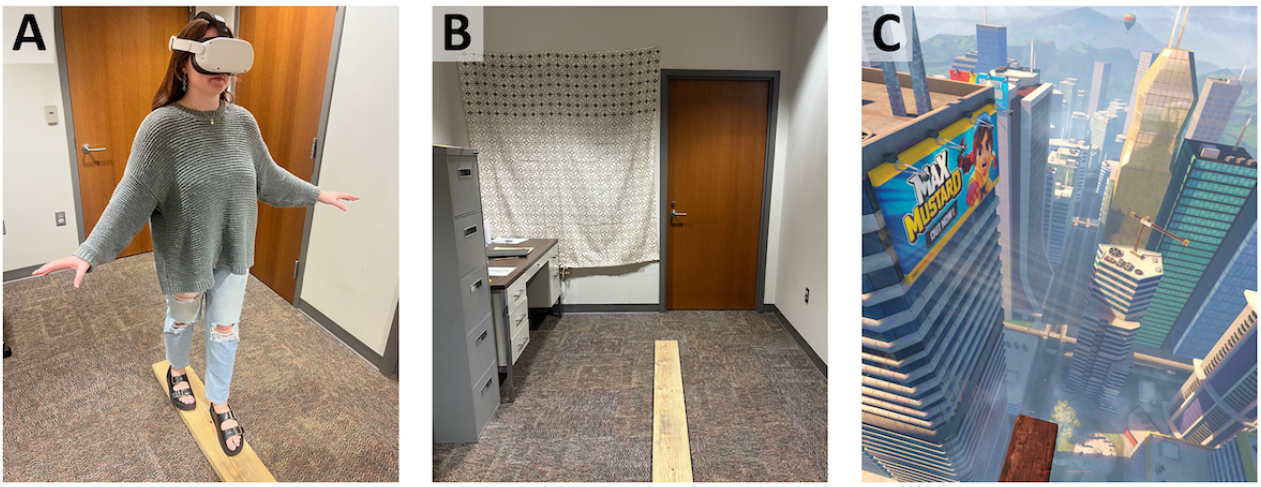
the use of a nasally administered medication (excepting steroids). Physiological data collection devices were unavailable in the beginning of the study, so those data were not collected from 21 participants. Technical challenges additionally limited data collection for heart rate and respiration (n=1), heart rate only (n=2), and respiration only (n=1). At least 1 participant did not feel well enough to complete the study and provided only demographic and personality data.

Procedure

Prior to the VR experience, participants provided demographic information and self-reports of anxiety, height-specific anxiety (major component of acrophobia), and impulsive sensation seeking. All self-report inventories were administered via Qualtrics. Participants also completed the behavioral sensation-seeking task. Participants were then guided through an immersive fear-inducing VR simulation of height exposure, with physiological recording initiated before the VR experience and continuing until the VR task was completed. Self-reported state anxiety was measured again near the end of the fear induction while in VR. Figure 1 illustrates the experimental procedures in a timeline format.

Figure 1. Experimental procedures. Undergraduate student participants were tested in the same manner in a pre-post intervention design. Intake included screening and informed consent, followed by a demographics questionnaire (eg, age, sex, childhood income, race). All procedures were completed within 60 minutes and were conducted in the same experiment room (pictured in Figure 2A and B). Behavioral sensation seeking was assessed with the Aroma Choice Task (ACT). Personality questionnaires included the State-Trait Anxiety Inventory for States (STAI-S), Acrophobia Questionnaire-Anxiety, and Zuckerman Kuhlman Personality Questionnaire (ZKPQ). The Richie's Plank Experience is described in detail in the text. Physiological data (heart rate and respiration) were recorded throughout virtual reality (VR).

Figure 2. Experimental environment and display. (**A**) All experimental procedures were conducted in the private quiet room shown, with participants' initial steps corresponding to the tactile experience of walking on a plank. (**B**) The researchers' view of the room and plank, and (**C**) the visual effects as displayed to participants. Wind noise corresponding to high altitudes was played through the headset speakers while walking on the plank. The tactile, visual, and auditory elements integrated for an immersive visceral simulation of walking on a plank from a city building at extreme height. Participants were oriented facing the plank at the onset of the paradigm.



Self-Report Inventories

Anxiety

Changes in self-reported anxiety before and during the experience indexed evoked fear. The State-Trait Anxiety Inventory for states (STAI-S) is a 20-item questionnaire rated on a Likert-type scale anchored by "not at all" (1) to "very much so" (4). Participants report how they currently feel (eg, *"I feel frightened"*). Total scores range from 20 to 80, with 80 indicating the highest anxiety levels [45]. This questionnaire assessed baseline and evoked anxiety, with the subtracted (Pre-Plank vs Plank) difference quantifying evoked anxiety. We changed the administration of the STAI-S during data collection to better capture the emotional state while still in VR. The first 21 participants completed the inventory on a laptop following the experience, but the last 36 participants were queried verbally while still in the headset (standing on the end of the virtual plank), and responses were recorded by the experimenter. "Plank," the post condition, refers to both ways of measurement. This change was provoked by the concern based on behavioral observation that STAI-S responses following the experience might be substantially influenced by relief, that is, anxiety alleviation, upon the termination of the fear-inducing experience. To ensure consistency, both the Pre-Plank and Plank STAI-S inventories were conducted verbally following this change.

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Height-Specific Anxiety

The Acrophobia Questionnaire-Anxiety is a 20-item questionnaire that poses hypothetical height-related fear scenarios (eg, "*looking down a stairway from several flights up*") and collects responses on a 7-point Likert-type scale anchored by "not at all anxious; calm and relaxed" (0) to "extremely anxious" (6). Total scores ranged from 0 to 120 with higher scores indicating greater levels of anxiety specifically related to heights, or acrophobia [46].

Impulsivity and Sensation Seeking

The Zuckerman Kuhlman Personality Questionnaire is a 50-item forced-choice inventory posing self-descriptive statements (eg, "*I often do things on impulse*"). The 5 subscales are impulsive sensation seeking, neuroticism-anxiety, aggression-hostility, activity, and sociability. Possible scores on each ranged from 1 to 10, with 10 indicating a high presence of the trait [47].

Behavioral Sensation Seeking

The Aroma Choice Task (ACT) is a validated behavioral test of sensation seeking that measures the relative preference for an intense, novel, varied, risky option versus a mild, safe, "boring" option, with odorants delivered in real time. Participants are instructed:

> *For the next 12 minutes, you will make choices about some smells. The choice labeled 'Standard' will likely be mild and pleasant. The choice labeled 'Varied' will likely be stronger and pleasant, but there is a chance that it will be unpleasant. Upon making a choice, please inhale deeply through your nose to receive the aroma.*

Choice ratio, the percentage of "Varied" choices out of a total of 20 binary choice trials (range: 0% - 100%), yields a single behavioral index reflecting behavioral sensation seeking (designed after self-reported sensation-seeking trait descriptions) [30,31]. The original ACT was developed with an air dilution olfactometer [36], but a simpler, manual version yielded analogous results [38]. We further modified the task to deliver 20 trials instead of the original 40, as our prior work indicated that the first 20 trials accurately capture the trait with lower participant burden [36].

Physiological Recording

Heart rate, respiration, and skin conductance were collected for 36 participants using the BioRadio (Great Lakes Neurotechnologies; Cleveland, OH, USA) and skin electrodes plus a respiratory inductance plethysmography belt, with data logged on a laptop computer. At least 1 researcher closely assisted the participant during VR to prevent collisions and stumbles. A second researcher entered live event markers (single keystrokes) that were logged in the BioRadio data stream as the participant progressed through the phases of the VR experience. Standardized breathing exercises (eg, Balban et al [48]) prior to VR were intended to mitigate physiological variability between participants. The "Pre-Plank" measurements included the anticipatory elevator ride up to altitude and the 20 seconds before stepping onto the plank (mean 0.74 [0.24] minutes; max 1.70). The "Plank" measurements comprised stepping onto the plank after the 20 seconds was complete and then walking the length of the plank and off into freefall (mean 1.88 [0.60] minutes; max 2.85). Skin conductance data were not analyzed.

Virtual Reality

The fear of falling from heights is an "innate" fear, that is, nonreliant on associative conditioning [29] or locomotion experience [49], and nearly universal [50], meaning it is highly generalizable and reliable for eliciting potent fear responses. An immersive height exposure simulation was delivered on the Meta Quest 2 head-mounted VR display. The Meta Quest 2 features 6 degrees of freedom, high refresh rate (up to 120 Hz), and adjustment for interpupillary distance [51,52]. These features, combined with limited movement and short VR duration (mean 2.90 [0.58] minutes, max 3.90), minimized the risk of VR sickness [53]. Nonetheless, participants were informed about the risk of VR sickness and were encouraged to notify the researcher at any time to end the simulation. No participants complained of VR sickness or feeling unwell due to the VR experience.

The immersive height exposure simulation was the "Richie's Plank Experience" [44] delivered with a Meta Quest 2 head-mounted VR display. This simulation is widely used in VR research on fear responses and behavior [43,54,55]. It has also been used to study risk-taking [56] and suicide willingness [57] and is even proposed as a psychological preparation for psychedelic experience [58]. The paradigm simulates an elevator ride to the top of a tall building, and upon the door opening, presents a cityscape view from heights (~80 stories). Participants walk onto, down the length of, and off the end of a wooden plank protruding from the skyscraper. The height illusion is conveyed by audio and visual simulation of extreme exposure to open space and reified with wind noise and birds flying below the participant. Immersion was maximized with haptic feedback from a real wooden plank (6' long "2×8" [2 m×4 cm×19 cm]) spatially registered to the virtual plank. The wooden plank was slightly warped and thus creaked and shifted with human weight. Although verbal instructions were provided as needed, researchers refrained from unnecessary verbal or physical interaction during the experience to preserve presence. A simulated participant (the first author) walks on the plank (Figure 2A) in the center of partitioned office space (Figure 2B), with the participants' view at heights illustrated in Figure 2C.

Analytical Strategy

Physiological data collected by the BioCapture (Great Lakes Neurotechnologies; Cleveland, OH, USA) software were modeled in VivoSense (version 3.4). VivoSense calculated the means of heart rate and respiration rates in 10-second bins. Changes in physiological measures were calculated as the average rate during anticipation of stepping on the plank (Plank) minus the baseline average (Pre-Plank). All statistical tests were performed in SPSS v29.0.2.0 (IBM). Analyses were stratified by sex as prior work demonstrated important interactions by sex between anxiety and sensation seeking [26] and by sex and elements of sensation seeking [30,59]. VR-induced increases in anxiety and physiological arousal were tested with paired *t* tests (2-tailed) between baseline "Pre-Plank" and the moment

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of stepping off the plank "Plank." Change scores were calculated for self-reported state anxiety and physiological measures (Plank minus Pre-Plank scores). These were tested for correlations with behavioral sensation seeking, each other, and height-specific anxiety. The potential effect of changing the STAI-S assessment method (computer vs verbal inside VR) was tested with independent-samples *t* tests (2-tailed). We tested for differences in participant characteristics of those with physiological recording versus without to assess potential effects on interpretation. *t* tests (2-tailed) of inhomogeneous variance (Levene test) were performed using the Welch *t* test (2-tailed). The false discovery rate was controlled with the Benjamini-Hochberg procedure [60], and limited to 5% (q<.05), by setting α=.0278 for individual tests in a priori hypotheses.

Results

Demographics and Personality

Tests evaluating baseline sex differences (χ^2 for nominal, *t* test [2-tailed] for continuous) reported were uncorrected and descriptive in nature. All in-text data are reported as mean (SD). Women reported higher baseline levels of anxiety than men did (neuroticism-anxiety, state anxiety, and height-related anxiety, P<.03; Table 1). No other sex differences were detected.

Table . Participant characteristics: demographics and personality (n=57).

Characteristic	Women (n=40)	Men (n=17)
Age (y), mean (SD)	20.23 (2.94)	20.06 (2.19)
Childhood income[a] (US $), median (IQR)	86,000 (35,000-127,000)	86k (35,000-141,000)
Race, n (%)		
American Indian	1 (3)	0 (0)
Asian	6 (15)	1 (6)
Black	6 (15)	2 (12)
Other/Unknown[b]	6 (15)	2 (12)
White	21 (53)	12 (71)
ZKPQ[c], mean (SD)		
Impulsive sensation seeking	3.82 (2.41)	4.35 (2.57)
Neuroticism-anxiety	5.50 (3.11)[d]	2.06 (2.08)
Aggression-hostility	4.24 (1.84)	3.88 (2.20)
Activity	5.05 (2.68)	4.41 (3.24)
Sociability	4.05 (2.52)	3.65 (3.18)
STAI-S[e], mean (SD)	34.26 (9.31)[f]	28.59 (7.87)
Acrophobia questionnaire-anxiety, mean (SD)	55.60 (18.78)[g]	43.12 (19.69)

[a]Reported as median and interquartile ranges representing the geometric means of the inventory ranges (<US $10,000, $10,000-$24,000, $25,000-$49,000, $50,000-$74,000, $75,000-$99,000, $100,000-$199,000, $200,000-$500,000, >$500,000).

[b]Hispanic ethnicity: n=5 identified as Other/Unknown, n=3 as White, n=1 as American Indian. Hispanic ethnicity did not differ by sex or race (χ^2, P>.71)

[c]ZKPQ: Zuckerman Kuhlman Personality Questionnaire subscales.

[d]$t_{44.7}$=4.83, P<.001.

[e]STAI-S: State Trait Anxiety, Inventory for states.

[f]t_{54}=2.19, P=.03.

[g]t_{55}=2.26, P=.03.

Evoked Fear: Increased Anxiety

The VR experience increased anxiety in both men (t_{16}=5.29, P<.001, 28.59 [7.87], and 44.76 [17.27], q<.05, Pre-Plank and Plank, respectively) and women (t_{38}=9.50, P<.001, q<.05, 34.26 [9.31] and 54.05 [14.51]; Figure 3A). The increase in anxiety was not significantly different before versus after the data collection method change (for more details, see the Anxiety section; P=.75).

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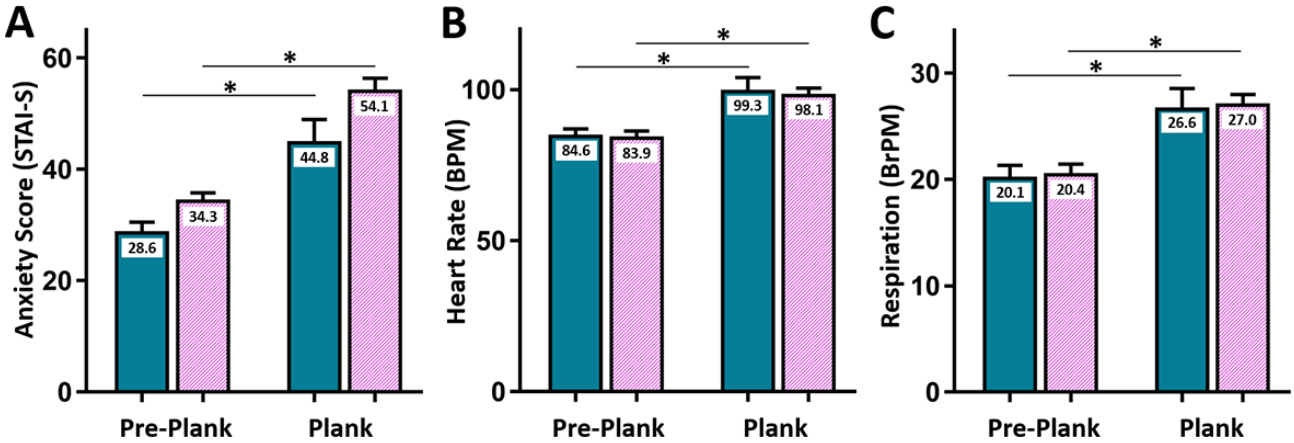
Figure 3. Effects of VR. Participants (solid cyan bars show the values for men, white/violet diagonal hash bars show the values for women) showed increased (**A**) anxiety states, (**B**) heart rate, and (**C**) respiration when on the plank relative to the Pre-Plank baseline. STAI-S=State trait anxiety inventory, State; BPM=beats per minute; BrPM=breaths per minute; *q<.05.



Physiological Arousal

In the 36 participants from whom physiological data were collected, the VR experience increased heart rate in both sexes (t_8=3.84, P=.005 for men t_{23}=6.99, P<.001 for women; q<.05; Figure 3B). Similarly, the VR experience increased respiration in both sexes (t_8=3.06, P=.02 for men and t_{24}=5.35, P<.001 for women; q<.05; Figure 3C). Of note, characteristics (Table 1) did not differ between participants with physiological data collected versus those without, q>.05 (11 tests); P=.53, P=.046, P=.24, P=.51, P=.84, P=.88, P=.62, P=.60, P=.25, P=.50, and P=.61, corresponding to childhood income, age, impulsive sensation seeking, aggression-hostility, activity, sociability, neuroticism-anxiety, AQ-anxiety, STAI, sex, and race, respectively.

Evoked Fear and Physiological Response

Fear (evoked state anxiety) did not correlate with changes in heart rate (P=.60 and .79 for men and women, respectively) nor respiration (P=.47 and .48) in the participants from whom physiological data were collected. Baseline anxiety was also uncorrelated with changes in heart rate (P=.70 and .29) and changes in respiration (P=.71 and .17).

Acrophobia and Evoked Fear

Fear of heights (acrophobia) was correlated with evoked state anxiety in men (r(15)=.606, P=.01) and women (r(38)=.410, P=.009, q<.05; Figure 4).

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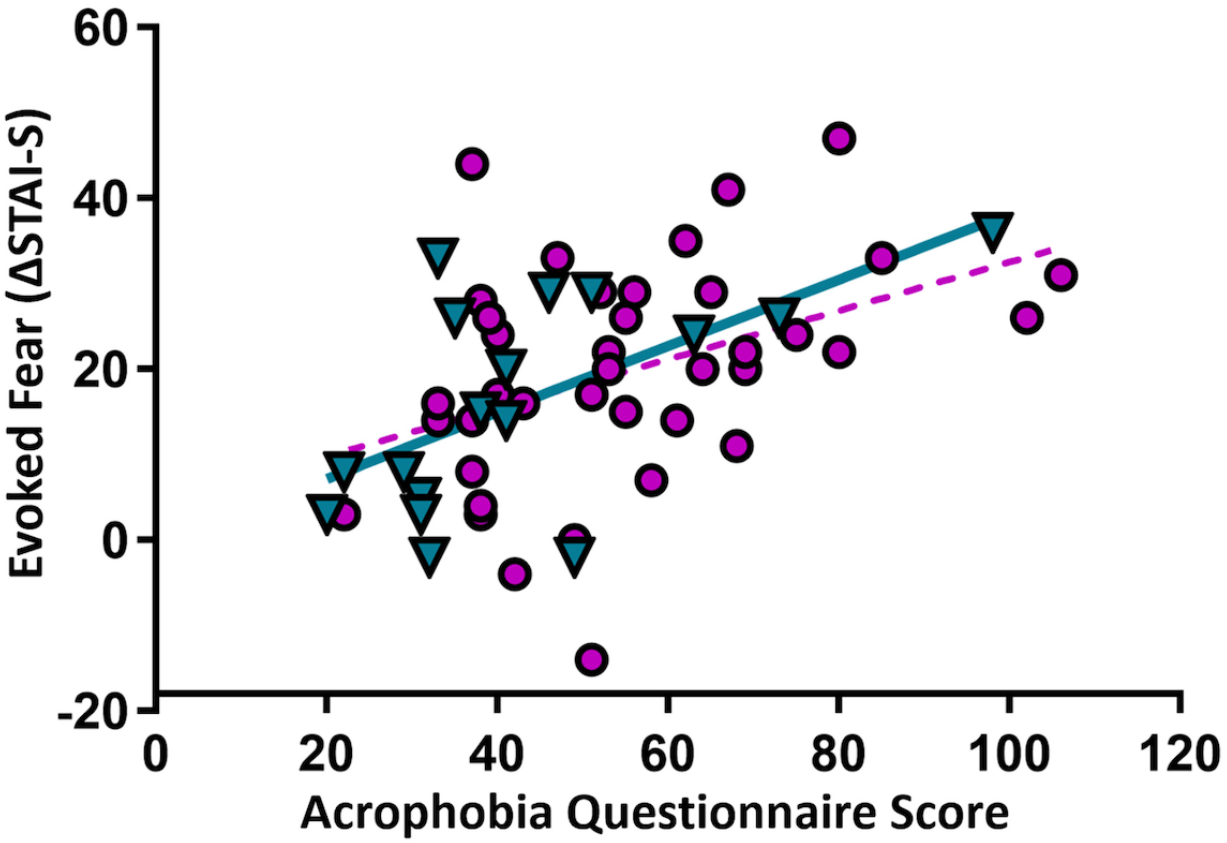
Figure 4. Height-related fear and fear response. Higher scores on the Acrophobia Questionnaire in both men (cyan triangles, solid line) and women (violet circles, dotted line) predicted greater anxiety reactivity to the virtual reality (VR) experience (r>.40, P<.011, q<.05). Regression lines illustrate strength and direction of associations. ΔSTAI-S: Plank minus Pre-Plank STAI-S scores.



Behavioral Sensation Seeking and Evoked Fear

High intensity preference (ACT scores) negatively correlated with evoked state anxiety (Δ STAI-S) in men (r(15)=−.559, P=.02, q<.05), but not in women (P=.67; Figure 5). Preference for high intensity was not correlated with baseline STAI-S scores in women (P=.61), although there was a trend in men (r(15)=−.465, P=.06).

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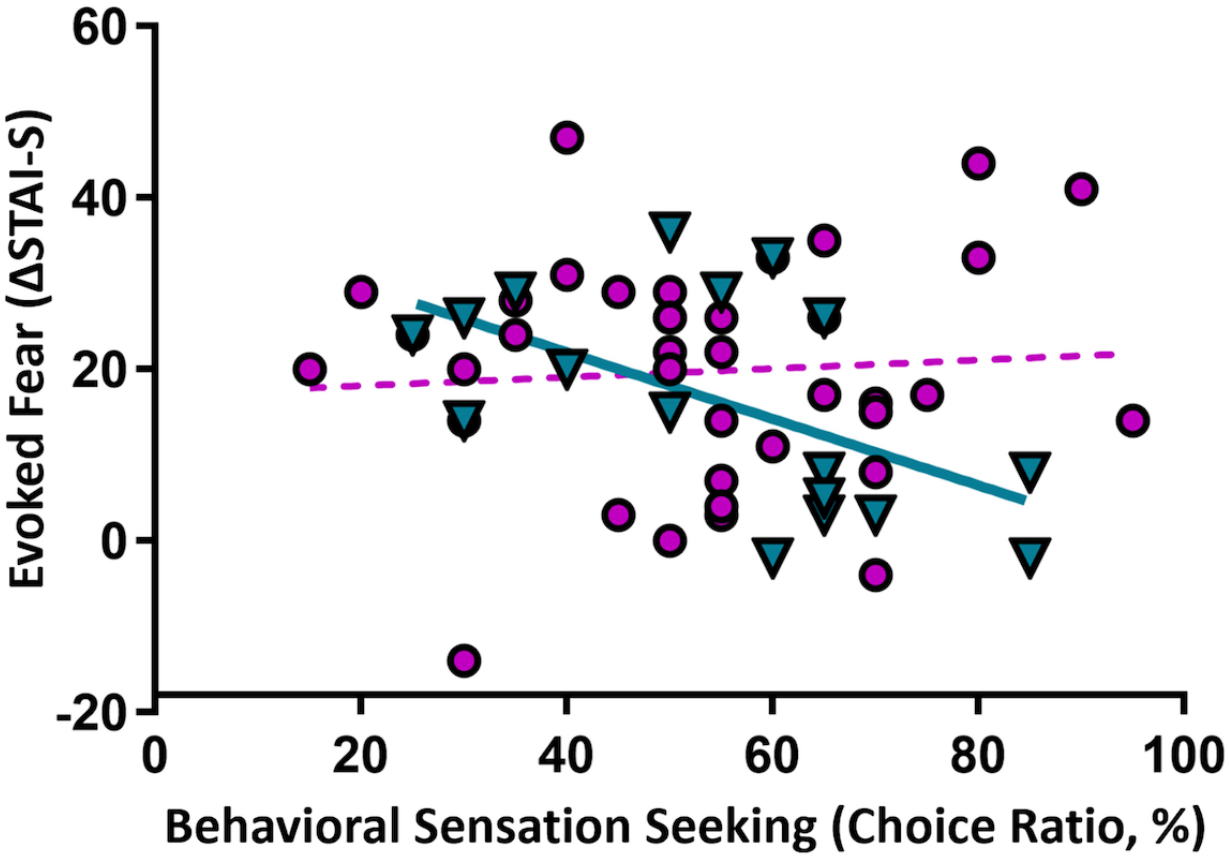
Figure 5. Sensation seeking and fear induction. Higher sensation seeking in men (cyan triangles, solid line) predicted lower anxiety response in virtual reality (VR; r=−.559, P=.02, q<.05), but not in women (violet circles, dotted line), P=.67. Regression lines illustrate strength and direction of associations. Choice ratio is the percentage of "varied" choices selected during the aroma choice task. ΔSTAI-S: Plank minus Pre-Plank STAI-S scores.



Behavioral Sensation Seeking and Physiological Fear Response

High intensity preference (ACT scores) negatively correlated with increased heart rate in men (r(7)=−.771, P=.02, q<.05), but not women (P=.54; Figure 6). Increased respiration was uncorrelated in both sexes (P>.28).

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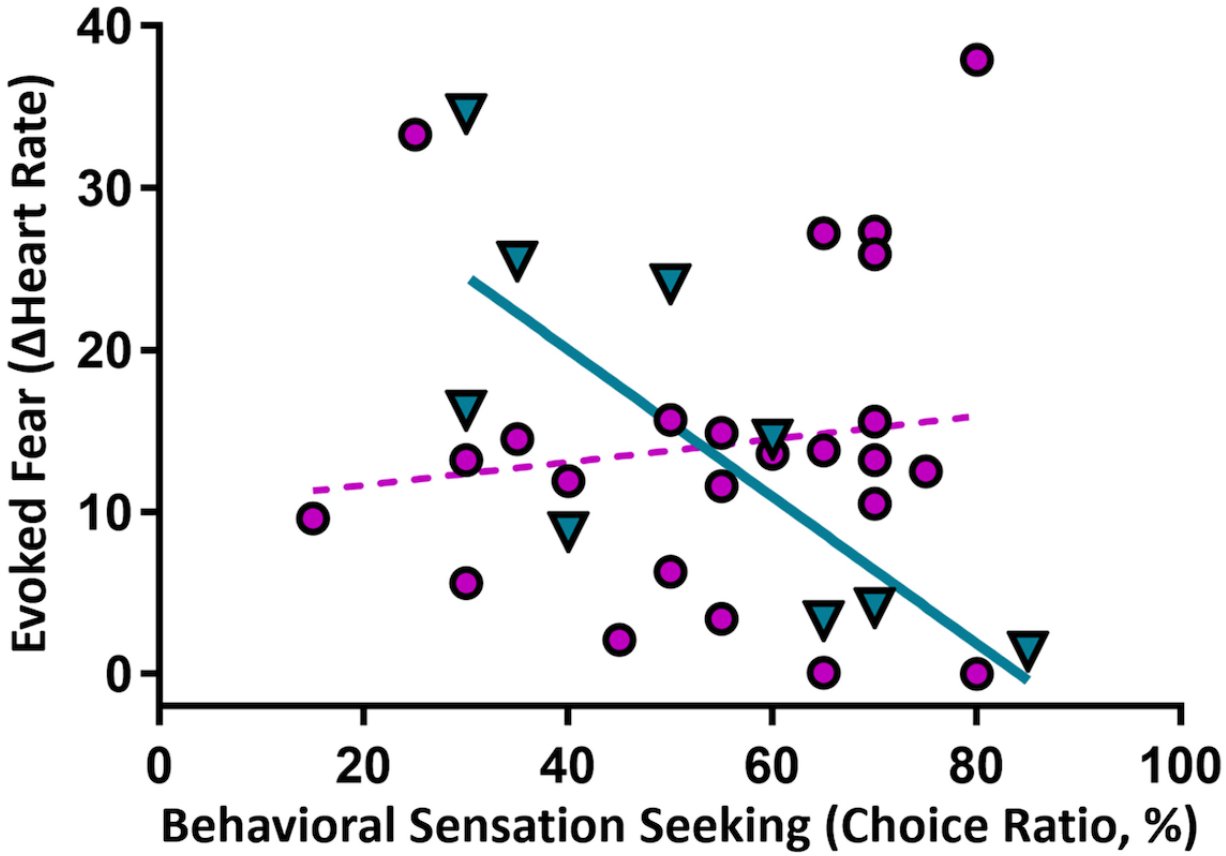
Figure 6. Sensation seeking and physiological fear response. Higher sensation seeking in men (cyan triangles, solid line) predicted lower heart rate reactivity to the virtual reality (VR) experience (r=−.771, P=.02, q<.05), but not in women (violet circles, dotted line), P=.54. Regression lines illustrate strength and direction of associations. Choice ratio is the percentage of "Varied" choices selected during the aroma choice task. ΔHeart Rate: Plank minus Pre-Plank heart rate measurements.



Behavioral and Self-Reported Sensation Seeking

High intensity preference did not correlate with self-reported sensation seeking in men (P=.47) or women (P=.72); collapsing across sex did not permit detection of an association (P=.89). See Table 2 for correlations of personality and behavioral metrics (uncorrected).

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Table . Systematic matrix of correlations.

	1	2	3	4	5	6	7	8	9	10
ZKPQ[a]										
1. ImpSS	—	0.082	0.286[b]	0.324[b]	−0.036	0.019	−0.173	−0.224	−0.027	0.212
2. Agg-Host		—	0.104	0.163	0.197	0.106	0.087	−0.134	0.238	0.349[b]
3. Act			—	0.202	0.210	−0.130	0.187	0.159	0.354[b]	0.127
4. Sy				—	−0.001	0.073	−0.097	0.059	0.229	0.261
5. N-Anx					—	−0.140	−0.332[b]	0.309[b]	−0.073	−0.142
Beh. SS (ACT[c])										
6. Choice ratio						—	−0.111	−0.236	−0.012	−0.029
Reported anxiety										
7. ΔS-TAI-S							—	0.483[d]	−0.039	−0.034
8. AQ-Anx								—	−0.318	−0.128
VR physiology										
9. HR Δ									—	0.137
10. Resp Δ										—

[a]ZKPQ: Zuckerman Kuhlman Personality Questionnaire subscales.

[b]Correlation is significant at $P<.05$.

[c]ACT: Aroma Choice Task.

[d]Correlation is significant at $P<.01$.

Discussion

Primary Findings

We found support for our hypotheses concerning VR's capacity to evoke fear (self-reported changes in state anxiety and physiological arousal) and the association between evoked fear and fear of heights. We found support for the negative association between evoked fear and behavioral sensation seeking in men, but not women. This unexpected finding is potentially due to higher trait anxiety scores in women, that is, imposing a ceiling effect and making associations between elicited anxiety and other traits difficult to detect. Interestingly, evoked fear measures were uncorrelated. Behavioral and self-reported sensation seeking were uncorrelated. These findings suggest that VR experiences possess sufficient ecological validity to elicit subjective and objective fear responses mirroring responses to real-world scenarios. Moreover, responses to the digital experience reflect associations with other traits (acrophobia and sensation seeking).

This study demonstrates the potential of VR for neuroscience and clinical research. VR continues to offer considerable promise for clinical and research applications alike. The expanding reach of VR is facilitated by better immersion technology, decreasing cost, creative applications, and wider adoption. While VR has long been used to administer exposure therapy [61-63] and treat pain [64-66], emergent applications target increasingly abstract constructs [67,68]. Germane to this study, VR applications effectively treat various anxiety disorders (eg, specific phobias, social anxiety disorder, panic disorder) in randomized controlled trials, producing effects comparable to conventional treatment and significantly better than passive controls [69]. In addition to promising efficacy data, providers and patients appear eager to adopt VR methods, as suggested by 2 recent reports on integrating VR in clinical practice [70,71]. The immersive nature of this nascent technology permits new avenues of investigation and permits research on humans that would be dangerous or impractical to study with real stimuli. We believe that the potential of VR to unite human and animal paradigms heralds a new translational era wherein strictly controlled animal neuroscience experiments can be accurately replicated in humans. For example, the elevated plus-maze—the gold standard in rodent anxiety research—can be instantiated for human participants [19] to connect basic neuroscience in rodents with human behavioral data. Other behavioral paradigms widely used in rodents, such as conditioned place preference, can now be accurately reproduced in humans using VR [72], producing convergent findings in both research contexts. Thus,

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the role and relevance of VR for both laboratory research and clinical practice are expected to grow substantially in the near future. The use of VR permits testing extant theoretical knowledge in more lifelike settings and experiences, and when paired with behavioral tests, yields increasingly objective outcomes.

VR can add knowledge to mature bodies of research, such as approach-avoidance, by presenting realistic simulations in humans. Approach-avoidance describes behavior that orients organisms toward positive and away from negative stimuli, respectively [73]. Approach-avoidance tendencies are likely rooted in evolutionary factors, primarily through sexually divergent selection pressure [74]; that is, reproductive fitness optimized by exploratory behaviors in men [75,76] and harm avoidance in women [77,78]. The extremes of the approach-avoidance continuum are marked by exaggerated attention on reward or threat cues [79]. These tendencies emerge from overactive brain reward or motivational systems [80] and underregulated brain threat systems [81] for approach, and conversely, overactive brain threat systems [82] and underactive brain reward systems [83] for avoidance. Sensation seeking and fear represent aspects of approach and avoidance, that is, opposing processes that modulate threat responses, such that high sensation seekers are less physiologically responsive to threat stimuli than low sensation seekers. One study testing fear responses found that high sensation seekers showed no response to threatening stimuli (versus control stimuli), whereas low sensation seekers produced an 8-fold increase in electromyographic response to threats [25]. No group difference in self-reported emotional reactivity was detected, further supporting the value of objective measurements.

Men are higher sensation seekers than women (particularly thrill or adventure seeking and disinhibition) [84,85], but the relationship between sensation seeking and fear appears to differ by sex. Investigating this relationship as an interaction with sex, Blankstein [26] found that the Sensation Seeking Scale (SSS) [23] total score negatively correlated with anxiety reactivity (Activity Preference Questionnaire) total and subscales (Social and Physical) at $r>.43$, $P<.01$ in men, but not in women ($r<.07$). However, a similar study found a number of negative correlations between the Sensation Seeking Scale and anxiety-related items (S-R Inventory) in both sexes [86], indicating mixed results in detecting sex interactions with approach-avoidance correlations. The lack of consilience in prior work might be explained by either (1) dependence on self-report inventories, with self-reported fear and sensation seeking often incongruent with objective measures [38,87], or (2) high anxiety and low sensation seeking in women producing restricted ranges (ceiling and floor effects), making correlations difficult to detect. Both factors potentially contribute together to the divergence. Future well-powered studies, ideally using precise behavioral tasks, should clarify these possible associations.

We did not detect correlations between self-reported fear and physiological responses to height exposure. While this is perhaps a surprising result, prior work suggests that self-reported fear does not necessarily reflect biological responses. In a real-world test, participants' self-reported fear of crime did not differ between walking down a dimly-lit path (vs well-lit control), but the dimly-lit path participants' heart rate increased by 17% ($P=.002$), with that in the controls remaining unchanged [87]. Even patients with anxiety disorders do not accurately report the degree of physiological responses to stress in laboratory tests [88,89]. This lack of concordance may be explained by individual differences in interoceptive ability [90]. The disconnection between self-reported traits and objective measures is also found in behavioral assessments of impulsivity [91], empathy [92], and risk preference [93], suggesting that the incongruence extends well beyond fear and anxiety. A recent report on associations between interoceptive ability and autobiographical memory [94] indicates that interoceptive perception (physical self-awareness) relates to episodic recall (cognitive self-awareness) and suggests the intriguing possibility that individual differences in these domains may be governed by some larger self-awareness meta factor.

Behavioral seeking and self-reported sensation seeking were uncorrelated in this sample. Existing findings offer scant data on this association due to the absence of behavioral sensation seeking tasks. Related traits such as impulsivity and risk-taking reveal low agreement between behavioral and self-reported assessment; for example, various measures of impulsivity are correlated at $r=\sim0.1$ in meta-analysis [91], and practically no relationship is observed between risk-taking measures [95]. Low reliability is observed in behavioral task data across domains [96]; in parallel, self-reported data suffer from various serious forms of bias [97]. The "jingle fallacy" (conflating interpretation of 2 measures because they have the same name) [98] exacerbates this problem. While the lack of convergence between behavioral and self-reported findings is perhaps unintuitive, this divergence between self-reported and behavioral data represents opportunities to discover additional features of personality traits. That is, important features of a given trait may not be fully captured by any single task or inventory.

Limitations

Some limitations should be acknowledged. First, the sample would benefit from more power. The homogeneity of the sample—reflecting typical undergraduates—is predominately female and White, precluding well-powered direct comparisons by sex and potentially limiting generalizability. Generalizability would be enhanced by a community sample with a more even sex distribution and a larger range of age and socioeconomic status. Finally, the truncated sample of subjects providing physiological data was suboptimal, as physiological data were only collected from 36 of the 57 participants, although the absence of significant differences between the subsamples somewhat mitigates this concern.

Conclusions

The current report demonstrates the potential use of VR for neuroscience and clinical research. Beyond research and education, VR is now well established as a clinically valuable tool in health care. The combination of using VR, objective measures (physiological recordings and behavioral tasks), and subjective measures (self-report) to investigate a behavioral health topic allows more rigorous investigation than any one of these approaches alone. Through these measures, we confirmed

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associations between self-reported experience and physiological fear in response to heights, in addition to behavioral patterns and personality related to sensation seeking. Further evidence of the disconnection between objective and self-reported methods was found, although this was perhaps unsurprising. We expect ever-wider adoption of VR applications and objective measures in the clinic and continued expansion in the laboratory research domain.

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Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

Conceptualization: BGO, BJD, CSJ, RCD
Formal analysis: BGO, CSJ, RCD
Investigation: BGO, CSJ, RCD
Methodology: BGO, BJD
Project administration: BGO, CSJ, RCD
Validation: BGO, CSJ, RCD
Visualization: BGO, CSJ, RCD
Writing – original draft: BGO, BJD, CSJ, RCD
Writing – review & editing: BGO, BJD, CSJ, RCD

Conflicts of Interest

None declared.

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Abbreviations

ACT: Aroma Choice Task
STAI-S: State Trait Anxiety Inventory-State
VR: virtual reality

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Evaluating the Potential of Metaverse to Elicit Therapy-Related Emotions Among Individuals With Depression: Controlled Pilot Study of Cognitive and Emotional Responses

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Abstract

Background: Depression, a prevalent mental health condition, affects millions worldwide. Many face significant barriers to accessing effective therapy. Metaverse has become a promising platform for addressing these challenges. Its 3D virtual environments allow users to engage through customizable avatars, supporting the elicitation of therapy-related emotions, an essential component of therapeutic interventions.

Objective: This pilot study investigates the potential of the Metaverse to elicit therapy-related emotional responses in individuals experiencing depression. The objectives are to assess emotional arousal, mental workload (MWL), and affective engagement during an emotional elicitation task in a Metaverse environment and compare them with those observed in a similar real-world setting.

Methods: We conducted a between-subjects experiment involving 28 participants: 14 had self-reported depression symptoms; 14 had minimal or no depression. Participants were assigned to a real-world environment or a Metaverse environment. Second Life (SL), a persistent 3D virtual world that utilizes human-like avatars for navigation, was the Metaverse environment. A desktop computer represented the real-world setting. Participants watched emotion-eliciting video clips to evoke amusement, anger, disgust, fear, and sadness. They reported their emotional arousal using the 16-item self-report inventory, MWL using the NASA Task Load Index, and emotional engagement using the Positive and Negative Affect Schedule.

Results: Regardless of the environment, participants with self-reported depression symptoms reported significantly higher amusement ($F_{1,24}$=4.882, P=.04; self-reported depression: mean 5.00, SD 2.481; minimal or no depression: mean 3.07, SD 1.940), anger ($F_{1,24}$=7.067, P=.01; self-reported depression: mean 4.79, SD 2.190; minimal or no depression: mean 2.71, SD 1.899), sadness ($F_{1,24}$=4.353, P=.048; self-reported depression: mean 5.21, SD 2.293; minimal or no depression: mean 3.50, SD 1.912), and perceived performance ($F_{1,24}$=4.939, P=.04; self-reported depression: mean 91.07, SD 90.302; minimal or no depression: mean 31.07, SD 36.278) than those with minimal or no depression. Participants with minimal or no depression reported lower perceived effort in the SL environment than in the real-world setting (SL: mean 40.71, SD 38.016; real world: mean 158.571, SD 120.411; P=.02), indicating Metaverse's potential to alleviate cognitive stress during emotionally eliciting tasks. There were no significant differences in perceived MWL or emotional engagement between the real-world and Metaverse settings.

Conclusions: Individuals with self-reported depression symptoms exhibited heightened emotional responses across environmental settings, indicating the Metaverse may potentially elicit emotional arousal comparable to that in traditional settings. Participants with minimal or no depression symptoms reported lower perceived effort in the Metaverse, suggesting that virtual environments may reduce cognitive strain during emotionally evocative tasks. The lack of significant differences in emotional arousal, overall MWL, or emotional engagement across environments tentatively suggests that the Metaverse may deliver emotional experiences like those of real-world contexts. Collectively, this provides preliminary evidence that screen-based Metaverse platforms can elicit emotional responses like those commonly engaged during therapeutic depression interventions.

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KEYWORDS

depression; emotional response; mental health; metaverse; second life

Introduction

Depressive Disorder and the Metaverse

Depressive disorder is a widespread mental health condition characterized by persistent feelings of sadness, low mood, and reduced interest or pleasure in activities [1-3]. According to the World Health Organization (WHO), as of 2023, depressive disorders and other mental health issues affected approximately 280 million people globally. It is estimated that around 3.8% of the global population experience depression, including 5% of adults (4% of men and 6% of women) and 5.7% of adults older than 60 years [2]. Symptoms of depression include irritability, prolonged disinterest or lack of pleasure in daily activities, impaired concentration and decision-making abilities, fatigue, sleep abnormalities, fluctuations in appetite and weight, pessimism, hopelessness, persistent sadness, restlessness, and thoughts of suicide [1,2,4-8]. The obstacles to accessing mental care services include workforce shortages, limited awareness and understanding, financial burdens, social stigma, and insufficient time for mental health discussions during medical appointments [5,9]. One way to overcome those obstacles is to use digital therapeutics or digital health in psychotherapy. Digital mental health services have evolved rapidly, aiming to enhance the efficiency and quality of health care services, including diagnosis, monitoring, treatment, and data management, through digital communication technologies [10,11]. However, most current digital mental health services only allow text or voice-based communication (eg, Tess [12], Woebot Health [13], WYSA [14]), which limits their capacity to elicit the emotional arousal and engagement that visually dynamic, real-time environments like those in the Metaverse can support.

The Metaverse is a 3D environment where users can interact with other users using avatars in a virtual world. It is a broad concept that uses a variety of technologies, including virtual reality, augmented reality, mixed reality, cryptocurrency, and the internet, to facilitate social interactions and user-generated content in a persistent digital environment across numerous domains, including economics, ecology, and health care [11,15-17]. This expansive Metaverse network allows users to experience a fully immersive environment, creating the sense of being inside the internet, where they can engage with other users, objects, and digital spaces as unique avatars, replicating real-world activities like socializing, working, and playing in a virtual setting [17,18]. By integrating physical and digital environments through devices such as tablets and smartphones, the Metaverse can connect various technologies, including artificial intelligence (AI), blockchain, tangible interfaces, and the Internet of Things, within 3D environments. This technology integration enables seamless interactions between virtual and real worlds, opening new possibilities for applications across multiple sectors, including mental health services [19].

Application of Metaverse in Mental Health

The Metaverse has recently gained attention as a promising platform for mental health interventions, offering safe, immersive experiences for therapies such as cognitive-behavioral therapy, exposure therapy, and other virtual reality–based treatments [20]. It has been applied in the treatment of depression, arachnophobia, astraphobia, ophidiophobia, post-traumatic stress disorder, anxiety, and eating disorders [16,20,21]. Individuals who feel lonely or stigmatized in their physical environment may find social support and a sense of community in the Metaverse. The controlled environment of the Metaverse allows patients to confront various stimuli causing anxiety or fear, such as public speaking, heights, or spiders [20]. Besides, users can interact with mental health professionals using customizable, anonymous avatars in simulated environments, which may fascinate individuals reluctant to seek in-person treatment [21,22]. Several studies have demonstrated the effectiveness of Metaverse-based interventions. Ezawa et al [23] found that a coach-led cognitive behavioral program delivered through the Metaverse app, Innerworld, significantly reduced depression and anxiety symptoms, with participants engaging as customizable avatars, fostering anonymity and engagement. Athar et al [24] developed a Metaverse-based AI recommendation system for patients with anxiety and depression that analyzed clinical notes and user-uploaded survey responses to predict condition severity and recommend treatments, including medications, psychiatrist referrals, and therapeutic activities. Buragohain et al [25] also found that Metaverse-based platforms such as NightWare, Freespira, EndeavorRx, and Sleepio can provide significant benefits, with clinical evidence supporting their effectiveness for treating conditions like post-traumatic stress disorder, anxiety, and attention deficit hyperactivity disorder. Beyond clinical applications, research indicates that users generally respond positively to the Metaverse. Mahmoud [15] found that people express positive reactions toward the Metaverse, with contentment, curiosity, and excitement being the most common sentiments, reflecting enthusiasm for its potential benefits in virtual environments. However, the Metaverse also brings notable risks. Within the Metaverse, individuals often feel more relaxed, which may increase their willingness to engage in deviant behaviors such as harassment, data exploitation, privacy breaches, and unregulated gambling [18] while also raising concerns about physical discomfort; emotional states such as nervousness; negative sentiment; and psychological effects, including mental fatigue and stress [15]. Despite growing interest and applications, little fundamental research has examined whether the Metaverse can elicit the range of emotions necessary for effective therapy without adversely affecting users' emotional or psychological states. To address this gap, this study evaluated the efficacy of the Metaverse using Second Life (SL), one of the most widely used Metaverse platforms, focusing on its ability to elicit emotional responses.

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SL as a Therapeutic Platform

SL is a persistent, 3D virtual world designed to simulate various aspects of real life. Created by Linden Research Inc and released in 2003, SL offers users a virtual world where they can create and personalize their online identities [18,26]. The platform has over 9 million registered accounts, more than 7.1 million total website visits, a daily average of 42,000 to 46,000 concurrent users, and 26,716 active regions [27]. Users can navigate the SL environment through human-like avatars, which are customizable and can be animated to express body language in unique and creative ways [26,28-33]. The virtual world consists of interconnected regions, including land, water, and sky, where users can freely alter their avatars' appearances and engage with other community members. It supports diverse modes of communication, including text messaging, voice chat, and note cards, creating a dynamic space for social engagement [32-34]. Users can also create, buy, or sell objects through the SL marketplace on the web using Linden Dollars, a virtual currency that can be exchanged for real-world money [26,28]. These features render SL a distinctive platform for creative expression and social interaction while also demonstrating substantial potential for telehealth and therapeutic applications.

SL has emerged as a promising Metaverse platform for therapeutic interventions and eliciting emotional experiences. Its virtual environments allow individuals to explore complex psychological and emotional processes in a safe, controlled setting. Research has shown that SL can support meaningful psychological and emotional experiences across diverse populations. For example, Davis and Alexanian [35] found that participants from disability-focused SL communities used child avatars to revisit past trauma, engage in nurturing interactions, and cultivate self-compassion while reducing emotional reactivity. Vanderburg et al [32] used SL to study emotional experiences, finding that its immersive and anonymous environment enabled participants to express emotions and reflect on trauma-related experiences. SL has also been applied in structured therapeutic contexts, showing benefits for relaxation and mindfulness [29], social cognition training in high-functioning autism [36], and cognitive-behavioral therapy for social anxiety disorder [33]. Additionally, SL has been reported as an engaging, interactive platform for creating dynamic, realistic scenarios. Rudolphi-Solero et al [34] found that participants in a virtual radiology competition rated SL as highly engaging, interactive, and valuable for learning and skill development. Similarly, Gout et al [28] developed an SL-based disaster simulation that enabled flexible, immersive training with realistic scenarios and physiological victim models, effectively supporting participants' experiential learning and practical skill acquisition. Despite these applications, few studies have specifically examined SL's effectiveness for eliciting emotional responses within therapeutic contexts. To address this gap, our study developed a dedicated SL island where participants could engage in activities using anonymous avatars that were designed to evoke emotional experiences. Considering SL's interactive nature, it was essential to investigate how such virtual environments may impact emotional arousal and cognitive load, particularly among individuals with depression.

Depression, Emotional Arousal, and Mental Load

Individuals with depression exhibit an abnormal physiological arousal pattern, known as hyperarousal, which is linked to emotional and cognitive responses. Emotional arousal encompasses the brain and bodily changes that occur in response to emotionally charged stimuli, serving as an indicator of how intensely a person reacts emotionally [37]. Depressed individuals also display heightened emotional reactivity, often interpreting external stimuli as more negative and stressful than nondepressed individuals [38]. This intensified sensitivity is further reinforced by repetitive negative thinking patterns, which can prolong emotional arousal and contribute to a recurring cycle of depressive symptoms [39]. Consistent with this pattern, Wenzler et al [38] observed that, when viewing negative emotion-eliciting stimuli, depressed participants rated them as more negative than healthy controls, highlighting their amplified subjective emotional responses. Additionally, recent research by Benau et al [40] indicated that individuals with depression showed increased sensitivity to emotional stimuli that are self-relevant. In contrast, their responses to non-self-relevant stimuli were reduced. This suggests that emotional reactivity in depression depends on the personal significance of the stimulus. Emotional processes are inherently multidimensional, including affective, physiological, and behavioral components, and are commonly studied through emotion-induction paradigms using pictures or film. Supporting the importance of stimulus realism in eliciting emotional responses, Berretz et al [41] found that highly realistic, specifically disgusting stimuli evoked stronger aversive emotional responses than less realistic ones, such as pictorial presentations. Depression is also associated with increased sensitivity to mental load and stress, which may prolong symptoms and impair functioning. Bowie et al [42] found that individuals with greater depression severity are more likely to disengage from cognitively demanding tasks. Similarly, Lerner et al [43] showed that stress is linked to depression and that depressed individuals exhibit impaired performance compared with non-depressed workers. Together, these findings highlight the need to better understand the emotional arousal and mental workload (MWL) of individuals with depression within Metaverse environments, informing its potential as an effective digital therapeutic intervention.

Research Gap and Study Aim

Although various studies have assessed the potential of Metaverse environments for mental health therapy, a significant research gap remains in investigating their effectiveness for eliciting targeted emotional responses, which may affect the realism of therapy. Specifically, there is a lack of studies examining the Metaverse platform's ability to evoke emotional reactions comparable to those experienced in real-world therapy environments. Furthermore, few studies have measured perceived MWL and emotional engagement while performing emotionally engaging tasks in Metaverse environments compared with real-world settings. This pilot study addressed this gap by evaluating the potential of a Metaverse environment to elicit emotions relevant to therapy and by investigating whether depression severity influences these responses. The objectives of this study were to assess individuals' emotional arousal, perception of MWL, and emotional engagement while

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performing an emotional elicitation task in a Metaverse setting or a real-world setting and to compare these measures between the two environments to determine the effectiveness of the Metaverse at eliciting emotions.

Methods

Study Design

In this study, we conducted a controlled experiment to evaluate the effectiveness of a Metaverse environment for eliciting emotional responses compared with a real-world setting. Participants were categorized as having minimal or no depression symptoms or self-reported depression symptoms based on their self-reported scores on the Patient Health Questionnaire-9 (PHQ-9) [44]. We utilized a 2 (environment: Metaverse and real world) × 2 (depression severity: minimal or no depression symptoms and self-reported depression) factorial design to assess the main and interaction effects of environment and depression severity on emotional arousal, perception of MWL, and emotional engagement while participants performed an emotional-eliciting task.

Real-World Settings

The real-world setting for this study consisted of a soundproof laboratory room located at Binghamton University. The room was furnished with a desktop computer, a table, and a chair. Participants were invited to the lab to watch the videos on the desktop using YouTube as the media platform. The layout of the real-world setting is shown in Figure 1A.

Figure 1. Experimental settings used in the study: (A) real-world laboratory environment, consisting of a soundproof room equipped with a desktop computer, table, and chair, where participants viewed the video stimuli on YouTube, and (B) Metaverse environment created on the Second Life platform, consisting of a virtual room modeled after a real-world setting and equipped with a projector, table, and chair, where participants viewed video stimuli via avatars.

(A) (B)

Metaverse Settings

For the Metaverse environment, we used the SL platform. A room replicating the real-world setting was created within the SL environment. This virtual room was equipped with a projector for video playback, as well as a table and a chair. Two customizable avatars were developed: One represented the researcher, and the other represented the participant. A short training video was provided to the participants beforehand to familiarize them with the SL system. This training video included instructions on navigation, communication through talking and chatting, and watching videos within the SL environment. The setup of the SL environment is shown in Figure 1B.

Emotional-Eliciting Task

In this experiment, we asked the participants to watch short emotional clips as an emotional-eliciting task. We selected 5 short videos to elicit emotions including amusement, anger, disgust, fear, and sadness. These emotions were chosen for their relevance to therapeutic applications for depression. The video clips were identified through a literature review of previous studies that successfully used these stimuli to evoke the targeted emotions. Table 1 describes each video clip and its associated emotion.

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Table . Description of emotional-eliciting video stimuli used in the experiment, summarizing the targeted emotion, film name, scene content used to provoke the intended emotional response, clip duration, and supporting reference.

Targeted emotion	Film name	Description of clip	Length (seconds)	Reference
Amusement	I Love Lucy	Clip of a candy factory where two women struggle with the rapid speed of a conveyor belt and start stuffing the chocolate candies into their mouths	178	[45]
Anger	My Bodyguard	Clip of a moment where two bullies attack a young boy, beat him, break his bike, and throw it into the water	249	[46]
Disgust	Pink Flamingos	Clip of a scene where a person eats dog feces	29	[46]
Fear	Silence of the Lambs	Clip of a scene where an FBI agent pursues a suspect into the basement and uncovers a decomposing corpse	216	[46]
Sadness	The Champ	Clip of a moment where a young boy tearfully calls out to a boxer, who, severely injured after a match, collapses in the locker room and takes his final breaths, leaving those around him devastated	158	[46]

Participant Recruitment

After receiving approval from the Institutional Review Board of Binghamton University, a brief informational leaflet about the study and contact information for the primary investigator and researcher were distributed across Binghamton University's physical and virtual locations. Inclusion criteria required the participants to be adults aged 18 years to 35 years, with or without prior experience with virtual environments. Exclusion criteria included uncorrectable visual impairments that prevented individuals from achieving normal or functional vision as well as severe motion sickness or a known intolerance to virtual environments. The researcher initially screened the interested individuals based on inclusion and exclusion criteria, and participants who met the inclusion criteria were invited to visit the Human Cognitive and Visual Behavior Lab at Binghamton University. We recruited 14 healthy individuals (with either no or minimal symptoms of depression), as well as 14 individuals with self-reported depressive symptoms.

Experimental Procedure

In the real-world setting, the experimental procedure was described upon the participants' arrival at the laboratory, and informed consent was obtained. Next, they were asked to complete the PHQ-9 questionnaire and provide demographic information, including age and gender. Participants were then instructed to complete the emotional elicitation task, which involved watching 5 emotional video clips on YouTube using a desktop computer. In this setting, communication between the researcher and participants occurred face to face.

For the Metaverse group, participants received a prerecorded training video with instructions on navigating SL, the Metaverse platform used in this study, and an electronic copy of the informed consent form. They were asked to review these materials, submit the signed informed consent, and reach out with any questions for clarification before attending their scheduled session. The SL environment was preconfigured on the laboratory's desktop computer, including a virtual room with a video playback projector. Upon arrival, participants were guided through the procedure virtually, with all communication between the researcher and participants conducted through SL avatars to eliminate direct interaction. After completing the PHQ-9 questionnaire and providing their demographic data, participants performed the emotional eliciting task of watching the 5 emotional video clips using the SL platform.

Participants from both groups completed the 16-item self-report inventory [46] to report their emotional arousal after watching each video clip. To reduce fatigue, a 2-minute rest period was provided between clips. The video clips were presented randomly for each participant to control for order effects. After viewing all 5 video clips and completing the associated self-report inventories, participants completed the NASA-Task Load Index (NASA-TLX) [47] and Positive and Negative Affect Schedule (PANAS) [48] questionnaires to report their perceived MWL and emotional engagement, respectively. Upon completing the experiment, each participant received a US $15 Amazon gift card for their time and participation.

Outcome Measures

Patient Health Questionnaire-9

The PHQ-9 [44], a brief self-report questionnaire, was used to screen for depression and its severity among participants. This 9-item measure includes 8 items addressing depressive

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symptoms and 1 item evaluating suicidal ideation, each corresponding to the diagnostic criteria for major depressive disorder as outlined in the *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition* (*DSM-IV*). Participants were asked to rate how frequently they experienced these symptoms over the past 2 weeks using a 4-point scale ranging from 0 (not at all) to 3 (nearly every day). The final PHQ-9 score, ranging from 0 to 27, indicates depression severity, with established thresholds used to categorize the level of depressive symptoms. Scores of 0 through 4 indicate minimal or no depression, 5 through 9 reflect mild depression, 10 through 14 indicate moderate depression, 15 through 19 represent moderately severe depression, and 20 through 27 signify severe depression. Additionally, the PHQ-9 includes an item that assesses functional impairment by asking participants who reported any symptoms, "How difficult have these problems made it for you to do your work, take care of things at home, or get along with other people?" [49]. For this study, participants scoring between 0 and 4 on the PHQ-9 were classified as healthy participants with minimal or no depressive symptoms and placed in the minimal or no depression group. In contrast, those scoring 5 or higher were categorized as experiencing self-reported depressive symptoms and placed in the self-reported depressive symptoms group.

16-Item Self-Report Inventory

This study used a 16-item self-report inventory to assess discrete emotions. The items included amusement, anger, arousal, confusion, contempt, contentment, disgust, embarrassment, fear, happiness, interest, pain, relief, sadness, surprise, and tension. Participants were asked to rate each item on a 9-point scale, ranging from 0 to 8, where 0 indicated no experience of the emotion and 8 represented the highest intensity of the emotion they felt. The order of the 16 items was randomized for each participant. This rating procedure was adapted from the study by Gross and Levenson [46].

NASA Task Load Index

The NASA-TLX [47], a multidimensional, survey-based tool, was used to collect subjective feedback on MWL following the emotional-eliciting task. The NASA-TLX includes 6 subscales: mental demand (MD), physical demand (PD), temporal demand (TD), frustration, effort, and performance. To assess MWL, participants rated each of the 6 subscales on 20-step bipolar scales based on their experience after completing the task. Each scale generated a score of 0 to 100, rounded to the nearest multiple of 5. To determine the weight of each subscale in overall MWL, participants completed 15 paired comparisons, representing all possible permutations of the 6 subscales. The overall MWL score was calculated as the weighted mean of the 6 dimensions, yielding a score between 0 and 100, where low scores indicate low MWL and high scores indicate high MWL [50].

Positive and Negative Affect Schedule

In this experiment, we used the PANAS [48], a widely used adjective-based questionnaire, to assess the participants' emotional engagement. The PANAS consists of 10 positive affect (PA) terms and 10 negative affect (NA) terms, which measure pleasurable feelings and distress or unpleasurable feelings toward a situation, respectively. The specific PA and NA terms used in the scale are listed in Textbox 1. To assess participants' emotional responses, they were asked to rate how much they experienced each of the 20 emotions after completing the task, using a Likert scale ranging from 1 to 5. Lower scores on the Likert scale indicated a weaker association with the specific term, while higher scores indicated a stronger association. The final PA and NA scores were calculated by summing the 10 positive and 10 negative terms, respectively [51].

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Textbox 1. Positive affect (PA) and negative affect (NA) terms from the Positive and Negative Affect Schedule (PANAS) scale used to assess emotional responses.

PA:

- Attentive
- Active
- Alert
- Excited
- Enthusiastic
- Determined
- Inspired
- Proud
- Interested
- Strong

NA:

- Hostile
- Irritable
- Ashamed
- Guilty
- Distressed
- Upset
- Scared
- Afraid
- Jittery
- Nervous

Data Analysis

Sample Size Calculation

An a priori power analysis was conducted using G*Power software to determine the required sample size. The effect size was estimated from pilot data (the means and SDs of the NASA-TLX scores) involving 5 participants in each group. Using a 1-tailed test with α=.05 and β=0.20, the required sample size was calculated as 5 participants in each group. To improve data accuracy, we included 14 participants in each group.

Statistical Analysis

We collected 4 sets of subjective data in this experiment: PHQ-9, 16-item self-report inventory, NASA-TLX, and PANAS. The PHQ-9 total score was used to classify participants into 2 categories based on depression severity: minimal or no depression and self-reported depression symptoms. For the 16-item self-report inventory, scores from 5 dimensions corresponding to the 5 video clips were analyzed (Table 2). All 6 subscales of the NASA-TLX, including MD, PD, TD, performance, effort, frustration, and the overall MWL, were evaluated. PANAS scores for PA and NA were calculated by summing each dimension's emotional factors. Table 2 lists the dependent and independent variables for this study. Data analysis was performed using SPSS version 28 (IBM Corp). To examine the effect of the independent variables on the dependent variables, a 2-way ANOVA was conducted. The threshold for statistical significance was set at P<.05. To compare the means for any significant main effect or interaction effect, we used the Tukey least significant difference (LSD) method.

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Table . List of independent and dependent variables in the experiment.

Variables	Items measured
Independent variables	
Environment	• Real world • Metaverse
Depression severity	• Minimal or no depression • Self-reported depression
Dependent variables	
16-item self-report inventory	• Amusement • Anger • Disgust • Fear • Sadness
NASA-TLX[a]	• Mental demand • Physical demand • Temporal demand • Performance • Effort • Frustration • Overall MWL[b]
PANAS[c]	• Positive affect • Negative affect

[a]NASA-TLX: NASA Task Load Index.

[b]MWL: mental workload.

[c]PANAS: Positive and Negative Affect Schedule.

Ethical Considerations

This study was reviewed and approved by the Institutional Review Board of Binghamton University (IRB ID: STUDY0000402; date of approval: July 19, 2023). All participants provided informed consent before participation. All collected data were de-identified before analysis. All collected data were stored on a password-protected computer, with no personally identifiable information. All participants received a US $15 Amazon gift card as a compliment upon completing their study session.

Results

Participants

We recruited 28 individuals, evenly divided into 2 groups based on their depression severity: minimal or no depression and self-reported depression. Participants were assigned to either the real-world or SL environment, with each condition including 7 participants from both depression severity groups. Demographic information for all participants is presented in Table 3.

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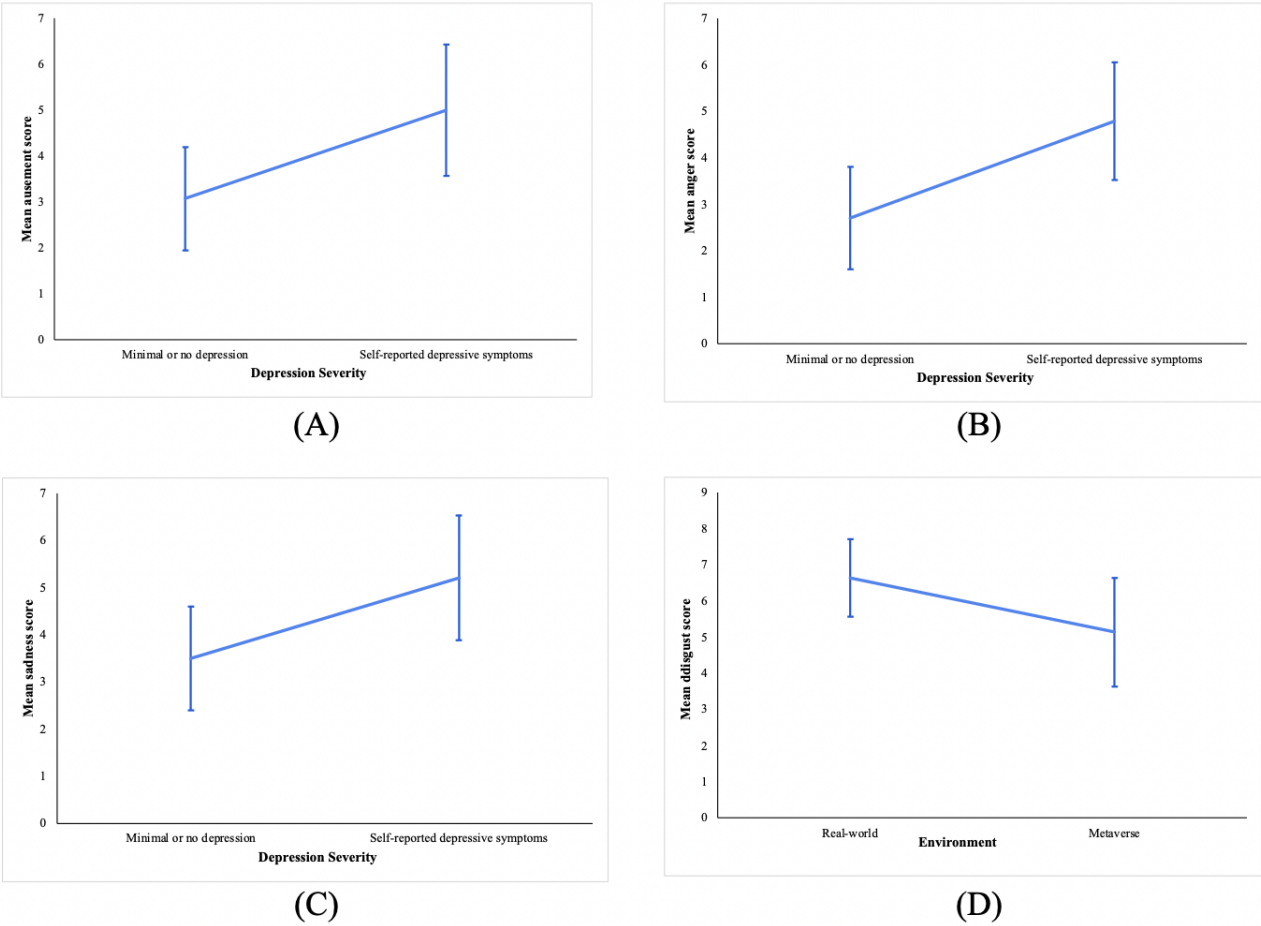
Table . Demographic characteristics of participants across the real-world and Second Life (SL) environment groups.

Environment	Depression level					
	Minimal or no depression		Self-reported depression		Total sample	
	Participants, n	Age (years), mean (SD)	Participants, n	Age (years), mean (SD)	Participants, n	Age (years), mean (SD)
Real world						
Gender						
Male	5	23.60 (5.68)	4	25.25 (1.50)	9	24.33 (4.21)
Female	2	20.50 (0.71)	3	23.00 (4.36)	5	22.00 (3.39)
Total sample	7	22.72 (4.89)	7	24.29 (2.98)	14	23.50 (3.98)
SL						
Gender						
Male	4	22.75 (4.79)	3	25.33 (2.08)	7	23.86 (3.85)
Female	3	27.33 (0.58)	4	22.75 (5.62)	7	24.72 (4.68)
Total sample	7	24.72 (4.19)	7	23.86 (4.38)	14	24.29 (4.14)

16-Item Self-Report Inventory

The 2-way between-subjects ANOVA showed that depression severity had a significant effect on the mean amusement scores reported by the participants ($F_{1,24}$=4.882, P=.04). Participants with minimal or no depression (mean 3.07, SD 1.940) reported a significantly lower mean amusement score than the participants with self-reported depression symptoms (self-reported depression: mean 5.00, SD 2.481; Figure 2A).

Figure 2. Effects of depression severity and environment on dependent variables showing mean scores and 95% CIs: (A) main effect of depression severity on mean amusement score, (B) main effect of depression severity on mean anger score, (C) main effect of depression severity on mean sadness score, and (D) main effect of environment on mean disgust score.



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The 2-way ANOVA showed that depression severity had a significant effect on the mean anger scores reported by the participants ($F_{1,24}$=7.067, P=.01). Participants with minimal or no depression (mean 2.71, SD 1.899) reported a significantly lower mean anger score than participants with self-reported depression symptoms (mean 4.79, SD 2.190; Figure 2B).

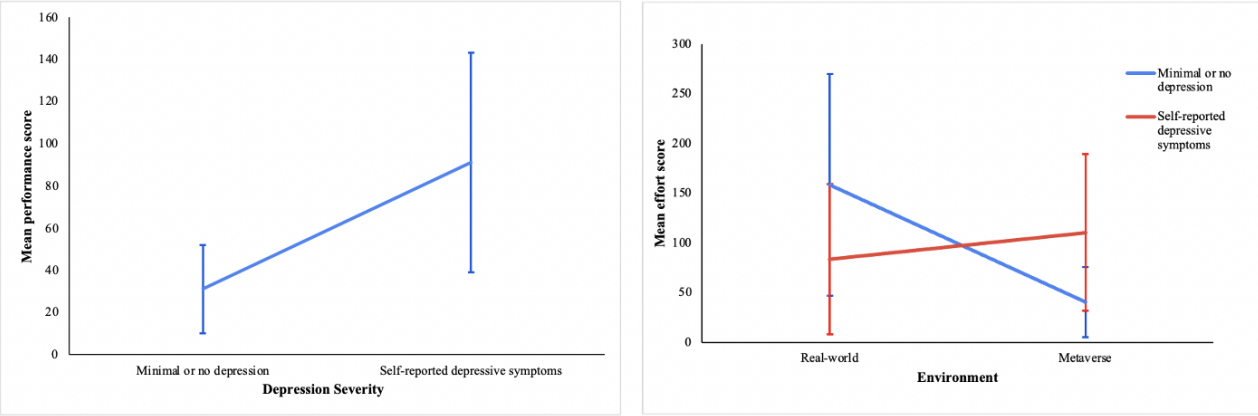
The 2-way ANOVA showed that depression severity had a significant effect on the mean sadness scores reported by the participants (F=4.353, P=.048). Participants with minimal or no depression (mean 3.50, SD 1.912) reported a significantly lower mean sadness score than participants with self-reported depression symptoms (mean 5.21, SD 2.293; Figure 2C).

The 2-way ANOVA revealed a trend suggesting that the environment may influence the mean disgust scores reported by the participants (F=3.128, P=.09). Participants who watched the video clips in a real-world environment (mean 6.64, SD 1.865) reported a higher mean disgust score than those who watched the video clips in a Metaverse environment (mean 5.14, SD 2.598; Figure 2D).

NASA Task Load Index

The 2-way ANOVA showed that depression severity had a significant effect on the mean performance scores reported by the participants (F=4.939, P=.04). Participants with minimal or no depression (mean 31.07, SD 36.278) reported a significantly lower mean performance score than participants with self-reported depression (mean 91.07, SD 90.302; Figure 3A).

Figure 3. Effects of depression severity and environment on dependent variables showing mean scores and 95% CIs: (A) main effect of depression severity on mean performance score and (B) interaction effect of environment and depression severity on mean effort score.



(A) (B)

The 2-way ANOVA showed that depression severity and environment had no significant main effect on the mean effort perceived by the participants; however, a significant interaction effect was discovered ($F_{1,24}$=4.931, P=.04). The Tukey LSD revealed that there was a significant difference between the mean effort score perceived by the participants with minimal or no depression in the 2 different environments, where participants in the real-world environment reported higher effort scores than those in the Metaverse environment (real world: mean 158.571, SD 120.441; P=.02; Figure 3B).

Positive and Negative Affect Schedule

The 2-way ANOVA showed that neither the environment nor the severity of depression significantly affected the mean PA and NA scores reported by the participants.

Discussion

Principal Findings

This study aimed to evaluate the potential of a Metaverse environment for eliciting therapeutic emotions compared with a real-world setting. Consistent with our aim, we compared individuals' emotional arousal, perception of MWL, and emotional engagement while performing an emotional elicitation task in the Metaverse and in a real-world setting. We recruited 28 participants, both with minimal or no depression symptoms and with self-reported depression symptoms, to perform the emotional-eliciting task in the Metaverse and real-world environments using the SL platform and a desktop computer, respectively. Subsequently, they rated their perceptions of emotional arousal, MWL, and emotional engagement immediately after completing the tasks. We found that depression severity significantly influenced emotional arousal, with individuals reporting depressive symptoms demonstrating higher levels of amusement, anger, and sadness across both environments. There was a nonsignificant trend suggesting higher disgust ratings in the real-world condition than in the Metaverse. We also observed a significant interaction between depression severity and environment on the perceived effort score, with participants with minimal or no depression reporting higher effort in the real-world environment than in the Metaverse. Additionally, a significant effect of depression severity was observed on the mean performance score, where participants with self-reported symptoms perceived higher performance than those with minimal or no depression. No significant differences were found between the environments or depression severity in overall MWL, MD, PD, TD, frustration, or emotional engagement, including PA and NA.

Interpretation and Implications

The elevated emotional responses among participants with self-reported depressive symptoms aligned with well-established

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evidence that individuals with depression often exhibit hyperarousal and intensified emotional reactivity, characterized by prolonged and heightened responses to emotional cues [37,38]. This finding is consistent with prior research indicating that individuals with depressive symptoms often experience heightened emotional arousal in response to stimuli [36,38]. Interestingly, disgust responses were slightly higher in the real-world environment than in the SL environment, which may align with prior evidence indicating that highly realistic or naturalistic stimuli tend to elicit stronger aversive responses, particularly for negatively valenced emotions such as disgust [41]. This result highlights that Metaverse environments may attenuate negative emotional arousal compared with real-world settings, suggesting a potential advantage in reducing such affective responses in ways that might be beneficial within therapeutic contexts, although such implications should be considered preliminary. However, the study did not find significant differences in emotional arousal (amusement, anger, sadness, and fear) as a function of environment. In therapeutic contexts, this pattern suggests that, although the Metaverse may help reduce certain aversive reactions, it may tentatively maintain typical emotional engagement, supporting its potential feasibility as an alternative therapeutic platform for future investigation.

An interesting finding of this study was the significant interaction effect of environment and depression severity on perceived effort. Participants with minimal or no depressive symptoms reported greater effort in the real world than in the Metaverse, suggesting that the Metaverse environment required less effort to achieve similar performance levels. Additionally, the absence of any significant differences in overall MWL, MD, PD, TD, or frustration between the real-world and Metaverse environments, as well as between the 2 groups, tentatively suggests that individuals with self-reported depression symptoms may not perceive these MWL dimensions differently from those without symptoms. One possible explanation is the high degree of task similarity between the two environments, as the Metaverse setting was intentionally designed to closely replicate the real-world tasks, potentially minimizing perceived differences. Another contributing factor may be the relatively brief exposure to each environment, combined with rest periods between sessions, which could have attenuated differences in workload perception. Interestingly, in our study, depression severity was significantly associated with higher perceived performance, which reflects a heightened perception of being successful in accomplishing the task among individuals with self-reported depression symptoms. In contrast to these findings, prior research indicates that depression is often associated with workload and impaired performance, which is aggravated by exposure to cognitive stressors such as high mental demands [42,43,52]. These findings suggest that, if designed carefully, the virtual environment of the Metaverse may potentially provide a comparable experience to the real world in terms of workload perception, even among individuals with varying mental health conditions.

Emotional engagement did not differ significantly between the Metaverse and real-world settings, suggesting that the environments may elicit comparable positive and negative responses. Although prior studies reported mixed emotional experiences in virtual environments [15], the Metaverse may help alleviate negative emotions such as fear or boredom by providing opportunities for exploration and fostering positive affective states like contentment, curiosity, and enthusiasm [15,53]. At the same time, extended engagement in virtual spaces may contribute to social alienation, with negative emotions potentially affecting real-life interactions and exacerbating isolation, anxiety, or identity-related challenges [18,20]. Additionally, interactions mediated through avatars cannot fully replicate tactile emotional expressions, such as handshakes or hugs, which may limit the depth of emotional engagement [18]. Future research should investigate specific interventions or design features to enhance emotional involvement and support well-being in Metaverse environments.

The Metaverse shows promise as a platform for eliciting emotional responses relevant to therapeutic contexts, supporting emotional arousal and engagement that may be comparable to real-world experiences. Its interactive nature may also reduce mental demands, providing a less effortful environment for individuals who may face challenges in traditional settings. These features suggest that Metaverse environments could potentially be leveraged to simulate real-life emotional situations in a controlled, adaptable, and accessible manner, aligning with the goal of facilitating emotional processing in therapeutic applications. Future research should explore personalized virtual interventions, guided emotional regulation exercises, and immersive exposure strategies to further enhance the potential of Metaverse-based experiences in supporting mental health.

Limitations

Several limitations of this study should be acknowledged. First, the study sample was restricted to adults aged 18 years to 35 years, which limits the generalizability of the findings to other age groups. Future studies should include a more diverse range of participants to determine whether the observed effects extend across different ages. Second, the study relied exclusively on self-reported measures of emotional arousal, MWL, and emotional engagement. Although these instruments provide subjective insights, they inherently limit the objectivity of the findings and may be influenced by individual biases. Incorporating complementary physiological measures, such as galvanic skin response and heart rate variability, alongside clinical data to detect depression could provide a more comprehensive and robust evaluation. Third, this study was a preliminary investigation with a small sample size: 7 participants per group in a 2×2 factorial design. The limited statistical power increases the likelihood of Type II errors, meaning that nonsignificant results cannot be interpreted as evidence of equivalence between the Metaverse and real-world conditions. As such, the findings should be viewed as initial, exploratory insights intended to inform future, larger-scale research rather than definitive conclusions. Fourth, the participants in the experiment were exposed to the real world and the Metaverse environment for a brief period. Prolonged exposure may reveal additional insights and more significant findings. Finally, the study utilized a single Metaverse platform, the SL. As an older, nonimmersive platform with dated graphics, SL may not fully capture the capabilities of immersive extended-reality systems.

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This limitation affects ecological validity, and findings may not generalize to other contemporary Metaverse platforms with higher levels of interactivity, realism, and immersion. Future research should examine multiple, advanced Metaverse platforms with varying levels of immersion or interactivity to evaluate their potential for therapeutic applications.

Conclusions

This pilot study provides early insight into how a screen-based Metaverse environment, Second Life, may support emotional elicitation tasks commonly used in therapeutic contexts. Although the findings suggest that participants reported tentatively comparable levels of emotional arousal, perceived MWL, and emotional engagement across the Metaverse and real-world settings, these results should be interpreted cautiously given the small sample size; reliance on self-report measures; and use of a nonimmersive, older virtual platform. This work is an initial step toward exploring the potential of Metaverse environments for future mental health research, such as helping to reduce emotional distress, provide controlled exposure, and alleviate cognitive stress, particularly for individuals who may find real-world environments overwhelming. It highlights the need for future studies with larger clinical samples and more ecologically valid therapeutic tasks.

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The authors declare the use of generative AI (GAI) in the research and writing process. According to the GAIDeT (Generative AI Delegation Taxonomy) taxonomy (2025), the following tasks were delegated to GAI tools under full human supervision. For proofreading and editing, the GAI tool used was: OpenAI, GPT-5 mini.

Responsibility for the final manuscript lies entirely with the authors.

GAI tools are not listed as authors and do not bear responsibility for the final outcomes.

Declaration was submitted by the authors.

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Data Availability

The deidentified datasets generated and analyzed during this study are available for research purposes [54]. All shared data excludes any personally identifiable information to ensure participant privacy.

Authors' Contributions

Conceptualization: CS, PM, MHC, LZ, AL
Data curation: FI
Formal analysis: FI
Funding acquisition: CS
Investigation: CS, PM, MHC, LZ, AL
Methodology: FI, CS, PM, MHC, LZ, AL
Project administration: CS
Resources: CS, PM, MHC, LZ, AL
Supervision: CS
Validation: CS, PM, MHC, LZ, AL
Visualization: FI
Writing - original draft: FI
Writing - review and editing: CS, PM, MHC, LZ, AL

Conflicts of Interest

None declared.

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Abbreviations

AI: artificial intelligence
DSM-IV: Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition
LSD: least significant difference
MWL: mental workload
NA: negative affect
NASA-TLX: NASA Task Load Index
PA: positive affect
PANAS: Positive and Negative Affect Schedule
PD: physical demand
SL: Second Life
TD: temporal demand
WHO: World Health Organization

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Augmented Reality in Enhancing Operating Room Crisis Checklist Adherence: Randomized Comparative Efficacy Study

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Abstract

Background: Effective crisis management in operating rooms (ORs) is crucial for patient safety. Despite their benefits, adherence to OR crisis checklists is often limited, highlighting the need for innovative solutions.

Objective: The objective of this study was to evaluate the efficacy of augmented reality (AR)-enhanced checklists in improving protocol adherence, compared to traditional paper checklists and no checklist scenarios during simulated OR crises.

Methods: This study was a randomized comparative efficacy study comparing the utility of AR checklists, paper checklists, and no checklist scenarios using 4 validated and simulated OR crises scenarios: asystolic cardiac arrest, air embolism, unexplained hypotension/hypoxia, and malignant hyperthermia. The study took place in a simulated OR setting and had applicability to the standard procedures in ORs, critical care units, and urgent care scenarios in the emergency department. To form the 24 OR teams, 50 professionals including 24 anesthesiologists, 24 nurses, 1 surgeon, and 1 scrub nurse from two academic hospitals were included. The primary outcome measured was the failure to adhere (FTA) rate for critical actions during simulated OR crises. Adherence was determined using retrospective video analysis involving 595 key processes evaluated across 24 surgical teams. Interrater reliability was assessed using a Cohen κ. Secondary outcomes included checklist usability and cognitive load, as measured by the low-frequency to high-frequency (LF/HF) ratio of the heart rate variability.

Results: The AR checklist group showed a significantly lower FTA rate (mean 15.1%, SD 5.77%) compared to the paper checklist (mean 8.32%, SD 5.65%; t_{23}=−2.08; P=.048) and the no checklist groups (mean 29.81%, SD 5.59%; t_{23}=−6.47; P<.001). The AR checklist also resulted in a higher LF/HF ratio for anesthesiologists ($F_{2,46}$=4.88; P=.02), showing a potential increase in the level of cognitive load. Survey data indicated positive receptions for both AR and paper checklists.

Conclusions: These results suggest that AR checklists could offer a viable method for enhancing adherence to critical care protocols. Although, further research is needed to fully assess their impact on clinical outcomes and to address any associated increase in cognitive load.

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KEYWORDS

augmented reality; operating room; crisis checklist; checklist; guideline adherence; quality improvement; patient safety; cardiac arrest; hypotension; hyperthermia; critical care; emergency department

Introduction

Unexpected crises in the operating room (OR), such as cardiac arrests or severe hemorrhages, create a critical situation in which surgical teams should deliver rapid and coordinated care with a time-sensitive order of actions listed in the OR crisis checklists [1-3]. Although these high-stakes, low-frequency crises may occur infrequently for any single practitioner, their cumulative incidence across hospitals underscores a significant challenge to patient safety and surgical outcomes [4-7]. The OR teams' ability to effectively manage these life-threatening complications depends on their preparedness in managing crises [8,9], training [10], and adherence to the validated crisis checklists [11].

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Presurgical checklists are used before surgery to ensure correct patient identification and procedure planning. In contrast, crisis management checklists guide surgical teams during emergencies, helping them respond quickly to life-threatening situations. While both checklists improve safety, this study focuses specifically on crisis management checklists, which aim to support decision-making during critical events in the OR.

The lack of adherence to the checklists negatively impacts surgical mortality rates and overall hospital performance [12]. Evidence suggests that adherence to established best practices during these critical moments is varied and often associated with a decay in the retention of essential skills and knowledge over time [13-16]. In many instances, the use of surgical safety checklists was associated with a reduction in morbidity and mortality, and they were integrated as a new standard of care [17,18]. The dynamic and high-pressure nature of surgical emergencies requires not only adherence to protocols but also the ability to quickly access and use complex information under cognitively demanding conditions [19-21]. However, even though adherence to these checklists is crucial, the traditional paper ones are often difficult to use effectively in such intense scenarios [22-24]. The low adoption of checklists underscores the need for innovative approaches to using checklists that fit with surgical workflows, enhancing protocol adherence without disrupting the clinical focus.

Augmented reality (AR) technology, by relaying important procedural information directly into the clinicians' vision [25-28], can enhance protocol adherence in medical settings [29-33]. Initial applications of AR in medication management and emergency trauma care have shown promise in reducing errors and guiding clinicians through complex procedures with enhanced clarity and efficiency [34-38]. This evidence positions AR as a potential technology for improving adherence to medical protocols [39-41]. However, the effectiveness of and adherence to AR-enhanced surgical checklists during OR crises has not been thoroughly studied.

This study aims to evaluate the efficacy of AR-enhanced checklists in improving protocol adherence by surgical teams during simulated OR crises. By comparing outcomes with the traditional paper checklists and scenarios without a checklist, the research seeks to provide evidence on AR's utility to reduce the failure to adhere (FTA) rate for crucial procedural steps when managing surgical crises, ultimately improving patient outcomes in the OR. We hypothesize that the AR-enhanced checklists will significantly reduce the FTA rate for crucial procedural steps compared to traditional paper checklists and no checklist scenarios.

Methods

Study Design

This prospective within-subject study aimed to compare the impact of AR checklists, traditional paper checklists, and no checklist conditions on managing OR crises (Figure 1). A detailed outline of team participation and the methodological framework is included in Multimedia Appendix 1. The development and rationale behind the crisis checklists, guided by surgical safety standards, have been detailed in a previous publication [14]. Teams, including anesthesia staff, OR nurses, and a mock surgeon, faced simulated intraoperative crises with randomized scenario assignments and checklist types. Before the main investigation, a pilot study tested the scenario fidelity and the AR checklist's practicality. Paper checklists were provided in booklet form and placed near the anesthesia machine and the circulating nurse's station, mirroring their accessibility in actual ORs. A summary and the checklists are available in sections 1 - 3 of Multimedia Appendix 1.

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Figure 1. Study overview diagram. (a) Checklists presented in an augmented reality interface using Microsoft HoloLens 2. (b) Study design scenarios including an augmented reality checklist, paper checklist, and no checklist.

Setups: The OR Checklists

We used OR crisis checklists for 4 critical scenarios: (1) asystolic cardiac arrest, (2) air embolism, (3) unexplained hypotension/hypoxia, and (4) malignant hyperthermia. These scenarios were derived from a comprehensive checklist development and testing process explained by Ziewacz et al [42] and were chosen for their clinical importance and feasibility for implementation in AR. Additionally, we followed the standardized approach used by Arriaga et al [14], which evaluated the efficacy of these checklists in improving adherence to lifesaving protocols through high-fidelity medical simulations. More details on the checklists and key processes evaluated to measure adherence to protocols can be found in section 3 of Multimedia Appendix 1.

Participants

Participants were recruited from 2 academic hospitals between October 2021, and September 2023. Each team comprised the anesthesia staff (including attending physicians and residents), OR nurses, one mock surgeon, and one scrub nurse, totaling 24 attending physicians and residents, 24 OR nurses, and one mock surgeon across 24 teams. Team formations were randomized. Each team dedicated an average of 3.5 hours within a single day to participate in a high-fidelity simulated OR environment. In the simulated OR, they encountered a series of crisis scenarios designed to test their adherence to critical and evidence-based practices. Recruitment of staff members was facilitated through sign-up sheets and random selection from those scheduled to work on designated study dates. Hospital departments arranged for staff to attend the simulation sessions instead of their regular workday. Hospital or department rules required that all anesthesia staff taking part had to have up-to-date certification

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in advanced cardiac life support. Each participant only took part in one study session.

Ethical Considerations

Ethical approval for this study was obtained from the Ministry of Health, Kuwait (IRBl: SKU-219328). Informed consent was obtained from all participants prior to their involvement in the study. Participants were informed about the study's objectives, procedures, and their rights, including the ability to withdraw at any point without any repercussions. All data collected during the study were deidentified and stored securely to ensure participant confidentiality. Data were anonymized during analysis to protect privacy, and access was restricted to authorized personnel only. No monetary or nonmonetary compensation was provided to participants for their involvement in this study. Identifiable features of participants were not captured in any images or supplementary materials.

Primary Outcome: FTA rate

The primary outcome was the FTA rate for 47 key lifesaving processes outlined in Multimedia Appendix 1. Adherence was evaluated and scored as either yes or no by 2 physician reviewers from our team (AA and RG) who observed and scored recorded simulation sessions. These sessions were recorded as synchronized videos on 2 screens for a comprehensive review. To ensure the accuracy of adherence scoring, interrater reliability was assessed. Any disagreements or uncertainties in scoring were reviewed by third reviewers (CP, HS) and were resolved. The primary variables included the checklist group and the medical crisis scenario. The primary aspect of the study was the measured FTA rates.

Secondary Outcomes

Cognitive Load

We used a Polar chest strap to collect interbeat interval data from participants during scenarios with an accuracy of 1 millisecond. Previous studies have shown that a low-frequency to high-frequency (LF/HF) ratio extracted from heart rate variability is a validated proxy for cognitive load [43-45], particularly when collected using chest wraps [46]. We used NeuroKit2, a toolbox for neurophysiological signal processing [47], to extract the LF/HF ratio from data aggregated into a 1-minute time window.

Participant Satisfaction and Usability

To evaluate the ease of use and the perceived effectiveness of the AR and paper checklists, we administered a structured survey adopted from Arriaga et al [14]. The survey assessed participants' preparedness, ease of use, readability, willingness to use the checklist in real scenarios, and perceived impact on the clinical flow during emergencies. Responses were captured on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), providing insights into participants' attitudes and perceptions across various aspects of checklist usage.

Statistical Analysis

Participant characteristics were presented by descriptive statistical analysis, which reported the number and percentage of participants across different roles and years of experience. To assess the consistency in observational scoring, the agreement between two reviewers on the adherence scores was quantified using a Cohen κ. The Shapiro-Wilk test was used to evaluate the normality of the data distribution. ANOVA was used to compare the efficacy of interventions across 3 groups and post hoc analyses were conducted to examine the checklist's efficacy across various scenarios. Participant satisfaction and usability were analyzed using descriptive statistics and reporting means and SD. The statistical analyses were performed using SAS with all P values being 2-sided and a threshold for statistical significance set at $P<.05$.

Results

Participants

A total of 50 participants, forming 24 teams, took part in this study, which included anesthesiologists (n=14), anesthesia residents (n=10), OR nurses (n=24), a surgical resident (n=1), and a scrub nurse (n=1). All anesthesia residents were in the early stages of their careers with 0 - 2 years of experience, and OR nurses included a more diverse range of experience, spanning from 0 - 8 years. Each team contained 1 mock surgeon and 1 surgical assistant (scrub nurse), who attended as stand-in participants to the operative field without participating in decision-making or survey completion; these stand-in staff members were not counted as participants. Participants' years of experience are summarized in Table 1.

Table . Participant's role and their years of experience.

Role	Years of experience in specialty, n (%)			
	0 - 2	2 - 8	>8	Unknown
Anesthesiologist				
Attending physician (n=14)	0 (0)	7 (50)	7 (50)	0 (0)
Anesthesia resident (n=10)	10 (100)	0 (0)	0 (0)	0 (0)
Operating room nurse (n=24)	6 (25)	12 (50)	3 (12.5)	3 (12.5)
Surgical resident (n=1)	(1) 100	0 (0)	0 (0)	0 (0)
Scrub nurse (n=1)	0 (0)	1 (100)	0 (0)	0 (0)

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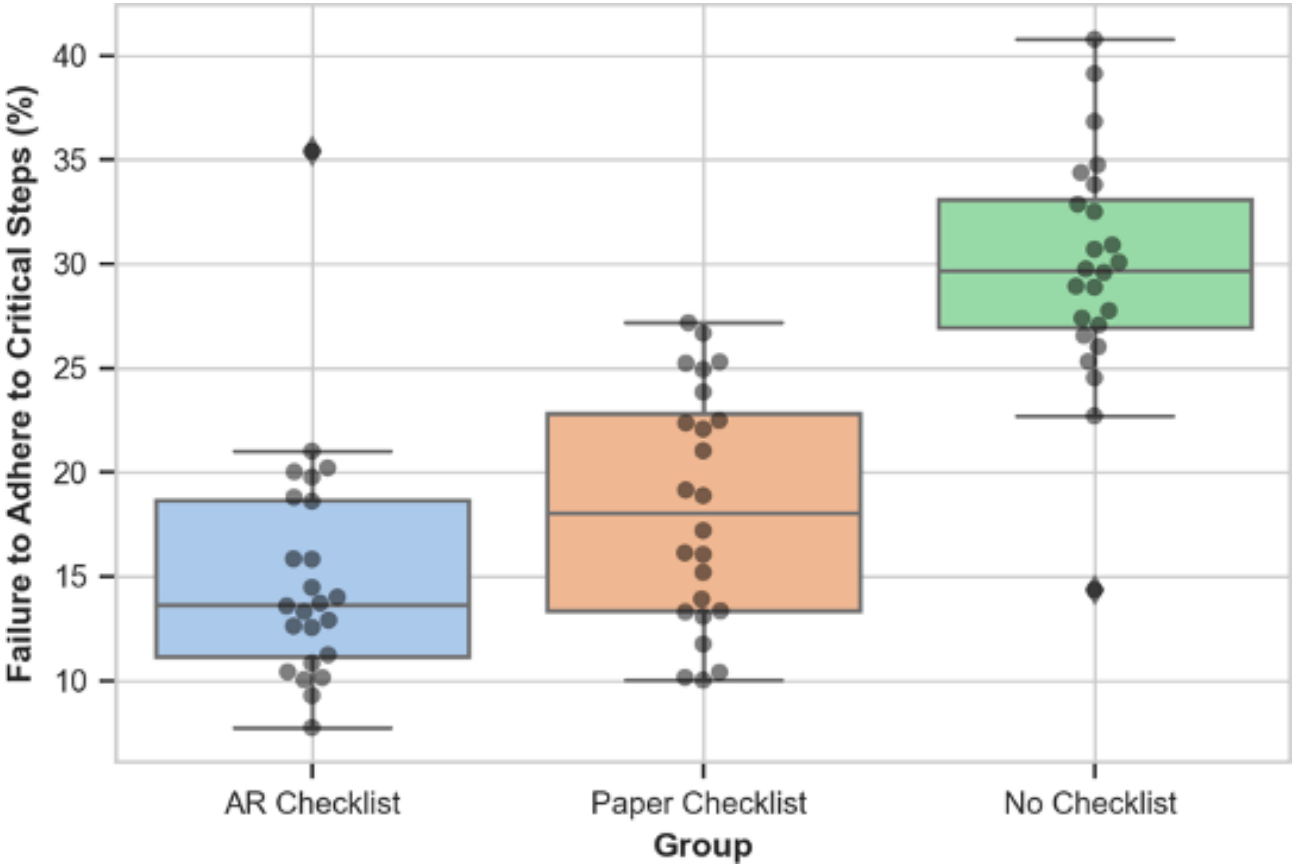
Adherence Rating

The assessment of adherence to key processes during the simulated scenarios demonstrated high interrater reliability among independent reviewer pairs, with Cohen κ values of ≥0.83 across all pairs. In instances where initial disagreement or uncertainty arose among the physician reviewers, consensus was reached through expert review with video replay. Out of a total of 595 key processes, evaluated across 24 teams for 25 key processes (excluding 8 key processes from one team that did not initiate the unexplained hypotension/hypoxia followed by an unstable bradycardia scenario), only 23 instances necessitated this expert review. The process of video replay facilitated immediate full agreement among all reviewers, highlighting the effectiveness of this approach in resolving ambiguities and ensuring accurate adherence assessment.

Comparing Groups Across All 4 Crisis Scenarios

ANOVA analysis showed significant differences in the FTA rate for critical steps among the 3 checklist groups ($F_{2,46}$=48.3; P<.001). Subsequent post hoc analysis showed the AR checklist group's mean FTA rate of 15.1% (SD 5.77%, 95% CI 13.50-16.70) was significantly lower than the paper checklist group's FTA rate of 18.32% (SD 5.65, 95% CI 16.75-19.89) and the no checklist group's FTA rate of 29.81% (SD 5.59, 95% CI 28.26-31.36). The AR group's FTA rate was significantly less than the no checklist group (t_{23}=−10.9; P<.001) and the paper checklist group (t_{23}=−2.08; P=.048). Moreover, the paper checklist group also had a significantly lower FTA rate compared to the no checklist group (t_{23}=−6.37; P<.001; Figure 2).

Figure 2. Failure to adhere to critical steps by condition type.



Comparing Groups for Individual Crisis Scenarios

Adherence to critical steps across various scenarios demonstrated significant differences among groups, with an ANOVA test showing distinct results for asystolic cardiac arrest ($F_{2,46}$=25.07; P<.001), air embolism ($F_{2,46}$=14.90; P<.001), malignant hyperthermia ($F_{2,46}$=12.33; P<.001), and unexplained hypotension/hypoxia ($F_{2,46}$=38.39; P<.001). Post hoc analyses indicated that, across these scenarios, the AR checklist group consistently exhibited significantly lower FTA rates compared to the no checklist group, with notable differences in asystolic cardiac arrest (t_{23}=−6.47; P<.001), air embolism (t_{23}=−4.45; P<.001), malignant hyperthermia (t_{23}=−4.79; P<.001), and unexplained hypotension/hypoxia (t_{23}=−10.57; P<.001). Comparisons between the AR and paper checklist groups were only significant for some scenarios, with slightly lower FTA rates for critical steps using the AR checklist in asystolic cardiac arrest (t_{23}=−2.65; P=.014) and unexplained hypotension/hypoxia (t_{23}=−2.10; P=.046). The paper checklist group also demonstrated significantly improved adherence over the no checklist condition in scenarios such as an air embolism (t_{23}=3.72; P<.001) and unexplained hypotension/hypoxia (t_{23}=5.40; P<.001; Figure 3).

While the AR checklist group demonstrated statistically significant differences in FTA rates compared to the paper

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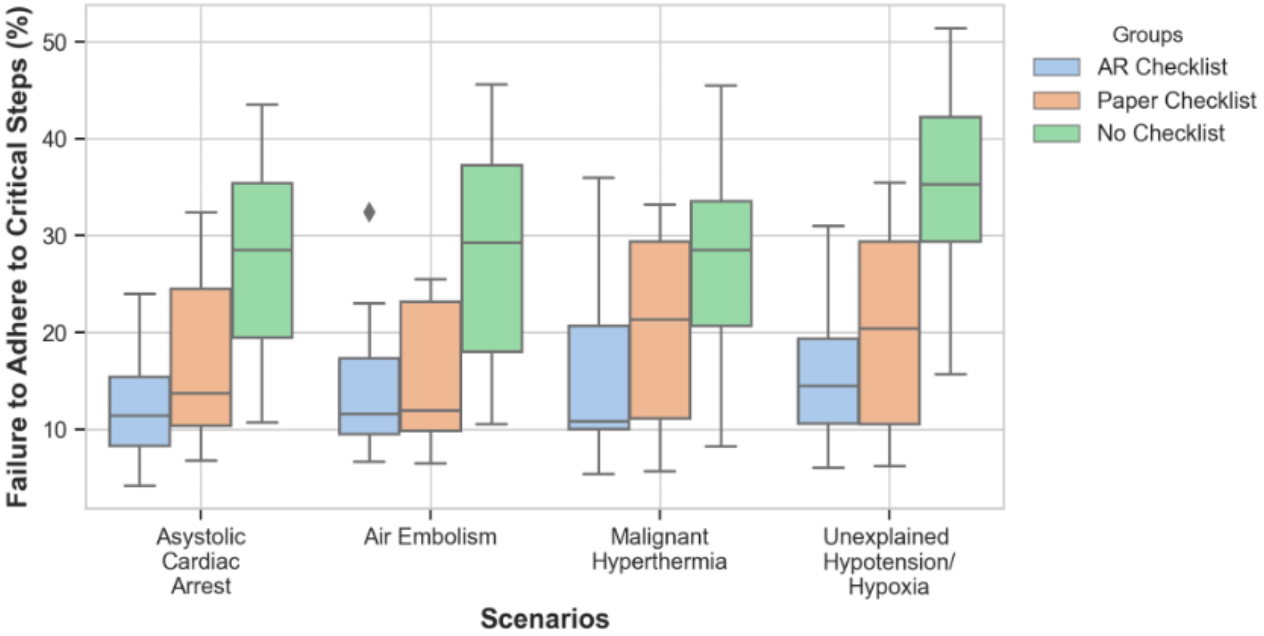
checklist group, it is important to note that this significance was observed by a narrow margin. Given the sample size, there remains the possibility that this effect could be influenced by chance, and further studies with larger sample sizes are necessary to confirm these findings.

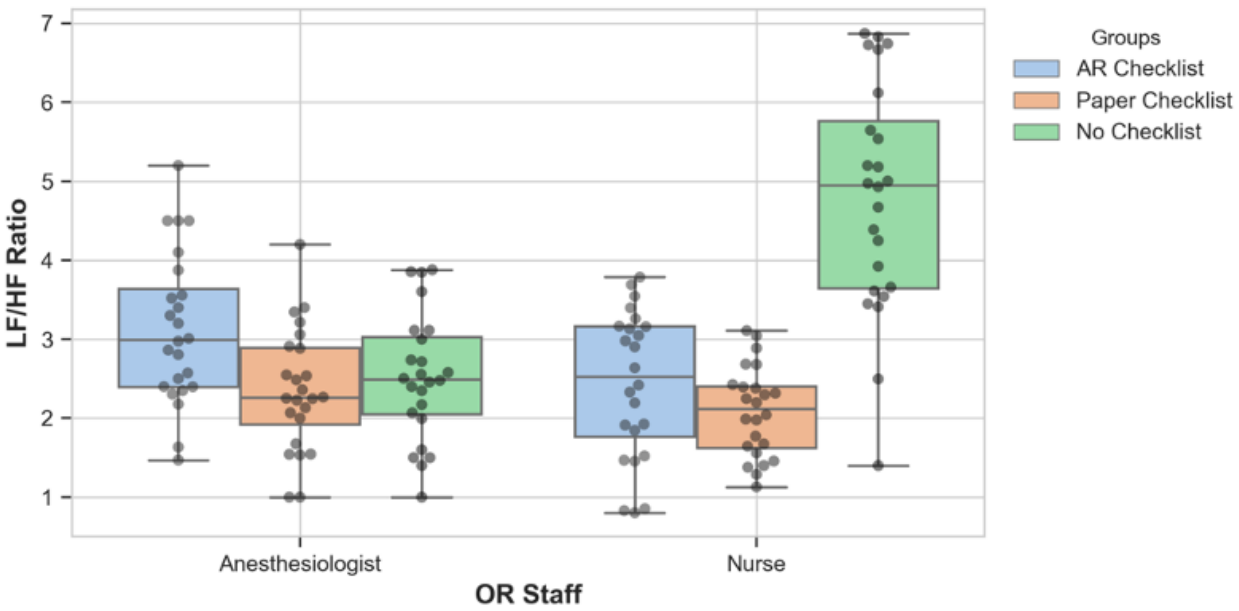
Figure 3. Failure to adhere to critical steps by scenario and group type. AR: augmented reality.



Cognitive Workload

For anesthesiologists, ANOVA results showed a significant effect of the checklist type on the LF/HF ratio ($F_{2,46}$=4.88; P=.02). In pairwise comparisons, the AR checklist group had a significantly higher LF/HF ratio compared to both the paper checklist and no checklist groups, suggesting a potential increase in cognitive load when using the AR checklist (P<.05; Figure 4). There was no significant difference in LF/HF ratio when comparing the paper checklist with no checklist groups, after adjusting for multiple comparisons. For nurses, the differences were significantly different ($F_{2,46}$=43.25; P<.001). The no checklist group had a significantly higher LF/HF ratio than the other two groups (P<.05). The AR checklist and paper checklist groups did not differ significantly.

Figure 4. Low-frequency to high-frequency ratio across operating room staff roles by checklist group. AR: augmented reality; LF/HF: low frequency to high frequency; OR: operating room.



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Survey

Survey responses showed that both AR and paper checklist groups viewed their respective checklists positively (Table 2). Participants in the AR checklist group rated the checklist's ability to help them feel prepared during the emergency scenario at a mean Likert score of 4.5 (SD 0.75), and the paper checklist group rated this at 4.3 (SD 0.82), indicating no significant difference between the groups. Participants expressed a strong willingness to use the checklists in real-life situations, with the AR group scoring a 4.6 (SD 0.70) and the paper group scoring a 4.4 (SD 0.75). When considering the disruption to the clinical flow of the operative emergency, the AR checklist group reported less disruption with a mean score of 4.5 (SD 0.90) compared to the paper checklist group's score of 4.2 (SD 1.00).

Table . Questionnaire response data from participants on checklist usability.

Statement	AR[a] checklist group (n=48), mean (SD)	Paper checklist group (n=48), mean (SD)	*P* value
The checklist helped me feel better prepared during the emergency scenario.	4.5 (0.75)	4.3 (0.82)	.13
The checklist was easy to use.	4.4 (0.80)	4.2 (0.85)	.09
I would use this checklist if I were presented with this operative emergency in real life.	4.6 (0.70)	4.4 (0.75)	.03
The checklist did not disrupt the clinical flow of the operative emergency.	4.5 (0.90)	4.2 (1.00)	.04
If I were having an operation and experienced this intraoperative emergency, I would want the checklist to be used.	4.7 (0.55)	4.6 (0.60)	.18

[a]AR: augmented reality.

Discussion

Principal Findings

Our findings show that AR checklist groups had a superior adherence to critical steps in crises when compared to the paper checklist groups and groups who did not use any checklist. These findings highlight AR's potential to improve OR staff's adherence to predefined protocols and ultimately improve patient outcomes. This improvement suggests that sending critical and time-sensitive information to clinicians' and OR staff's field of view may help with faster and more precise decision-making in critical situations and emergencies. Considering a day-by-day improvement in technology, this will have the potential to set the ground for an extended and more effective AR checklist intervention in many other critical scenarios. This potential benefit is in line with a comparison of the AR checklist versus the traditional checklist in other health care applications [29,30]. The benefit of AR checklists, particularly in comparison with non-AR alternatives, underscores the technology's capacity to augment traditional safety measures.

It is also important to note that while the AR checklist group had a clear superiority over the no checklist group, the margin of improvement was modest when it was compared to the paper checklist group. In this comparison, the differences were not always statistically significant across different scenarios. These findings suggest that AR technology may not offer the same improvement in all clinical scenarios over the paper checklists. Considering the low sample size and extensive subgroup analysis, it is reasonable to suggest that AR's real-world application and its superiority over conventional methods warrant further examination. We also observed variation in team performance, as highlighted in Figure 1 of Multimedia Appendix 1. Some of this variation may be attributed to an order effect, where teams became more familiar with the simulation environment over time. This potential bias should be considered when interpreting the results, and future studies could include randomization or counterbalancing to mitigate this effect.

The feedback from participants indicated a high level of acceptance and perceived utility of AR checklists in crisis scenarios, pointing to the potential for AR to integrate effectively into surgical workflows. However, the nuanced performance improvements highlight the need for a tailored approach to technological integration in health care, where the specific context and user needs dictate the effectiveness of such alternatives [48-50]. The study's results align with broader trends in medical and high-risk industries, where checklists have long been recognized for their role in promoting adherence to best practices and enhancing outcomes [51-53]. Just as checklists have transformed safety protocols in aviation and nuclear power, AR checklists hold promise for surgical settings. Nonetheless, the adaptation of these tools in medicine, particularly in the high-stakes environment of the OR, requires careful consideration of design, implementation, and training to ensure they meet the unique demands of health care providers and patients.

A key consideration emerging from our research is the differential impact of AR on the cognitive load among OR staff. Anesthesiologists using the AR checklist have shown a higher LF/HF ratio, which may be associated with a higher level of cognitive load when compared to the paper and no checklist

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groups. While we initially interpreted the higher LF/HF ratio in the AR checklist group as a sign of increased cognitive burden, it is also possible that this reflects heightened cognitive engagement. The AR checklist may stimulate more focused attention on the OR environment and monitoring, compared to the paper checklist, which could be perceived as more distracting. This alternative interpretation suggests that the AR condition may enhance attentional focus in a high-stakes environment, and further research is needed to clarify the relationship between LF/HF ratio and cognitive engagement.

It is an important finding that AR technology may improve adherence but simultaneously may add a cognitive burden [54,55] that adversely affects clinicians' behavior under cognitively demanding conditions. This variability in cognitive impact across different OR roles underscores the importance of designing AR applications that are tailored to the diverse needs and cognitive capacities of surgical teams. Future studies should also include qualitative methods to capture participants' experiences with AR and paper checklists. Combining this with quantitative data will provide a more complete understanding [56].

Limitations

This study has several limitations that should be considered. First, the study was conducted in a simulation setting that may not necessarily reflect the complexity of the OR environment. Second, our sample size was relatively small with a limited statistical power that prevented us from confidently performing subcategory analysis and extracting minor differences between groups. Larger studies with more diverse groups of clinicians and more scenario variability are needed to allow for subgroup analyses and to look for potential impacts on certain groups of clinicians or crisis scenarios. Third, the integration of AR technology into clinical practice raises questions about cost, accessibility, and the need for specialized training [57]. The development of best practices for the implementation and customization of AR checklists will be crucial to their successful adoption in surgical care. Last, we recognize that *P* values alone should not be taken as conclusive evidence of AR's superiority. The narrow statistical margin highlights the need for further validation through larger studies to confirm its efficacy.

Conclusion

Our study showed that the use of AR-enhanced checklists significantly improved adherence to critical procedural steps during simulated OR crises compared to both traditional paper checklists and scenarios without a checklist. These findings are promising as they may contribute to the patient's safety and outcomes. However, while the benefits of AR are promising, our findings also indicate a potential increase in cognitive load among clinicians, particularly anesthesiologists. Future studies should aim to optimize AR interfaces to minimize cognitive demands and validate these results in real-world settings. Addressing the balance between improved protocol adherence and cognitive load will be crucial for integrating AR effectively in high-stakes environments like the OR.

Conflicts of Interest

AG is the Medical Director of Ultrasight.

Multimedia Appendix 1
Supplementary materials on the development and application of augmented reality checklists for crisis management in clinical settings.
[DOCX File, 106 KB - xr_v2i1e60792_app1.docx]

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Abbreviations

AR: augmented reality
FTA: failure to adhere
LF/HF: low-frequency to high-frequency
OR: operating room

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Extended Reality Biofeedback for Functional Upper Limb Weakness: Mixed Methods Usability Evaluation

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Abstract

Background: The perception–action cycle enables humans to adapt their behaviors by integrating sensory feedback into motor actions. Functional neurological disorder (FND) disrupts this cycle, leading to maladaptive motor responses and a diminished sense of agency. FND includes functional seizures, movement disorders, and cognitive impairments, significantly affecting quality of life. Recent advancements in extended reality (XR) neurotechnologies provide opportunities for novel rehabilitation approaches, leveraging visual and haptic feedback to retrain motor control and restore agency in individuals with functional limb weakness.

Objective: This study aimed to co-design and evaluate an XR-based biofeedback platform for upper-limb rehabilitation in FND, incorporating multisensory feedback (visual and haptic) to enhance motor retraining.

Methods: A mixed methods design was used. In phase 1, a Delphi survey (N=20, patients with FND) identified key user requirements, emphasizing customizability, real-time feedback, accessibility, and comfort. These insights guided the codevelopment of an XR biofeedback platform. In phase 2, a co-design workshop with 6 participants (3 FND patient representatives and 3 health care professionals) evaluated the usability of 3 XR training tasks: virtual reality (VR) relaxation task, a guided meditation in a VR calming environment; XR position feedback task (“Hoop Hustle”), a VR-based motion task requiring arm movements to interact with virtual objects, providing real-time positional biofeedback; and XR force feedback task, a haptic robot-assisted exercise using the Human Robotix System (HRX-1) haptic device, applying resistive forces to guide upper limb movements. Participants completed system usability scale (SUS) questionnaires and provided qualitative feedback, which was analyzed using NVivo (QSR International) thematic analysis.

Results: The XR position feedback task achieved the highest usability ratings, with 4 out of 6 participants scoring it above 85, indicating “excellent” usability. The VR relaxation task received polarized scores: 2 participants rated it highly (90 and 87.5), while 3 scored it poorly (mid-40s), citing motion discomfort and disengagement. The XR force feedback task had mixed usability outcomes (SUS range: 27.5 - 95.0), with 1 participant with functional dystonia struggling significantly (SUS 27.5), while others rated it between 62.5 and 95.0. Qualitative feedback emphasized comfort (lighter headsets and better ergonomic design), immersion and content quality (clearer visuals and reduced distracting audio prompts), personalization (adjustable settings for speed, difficulty, and force resistance), and accessibility (cost concerns and home usability considerations). Overall, participants viewed the XR biofeedback platform as highly promising but in need of fine-tuning.

Conclusions: This study demonstrates the feasibility and usability of an XR neurotechnology platform for FND rehabilitation, with strong acceptance of XR position feedback, mixed reactions to VR relaxation, and individual-specific usability outcomes for the force feedback task. Findings underscore the need for personalization features and hardware refinement. Future work will focus on enhancing usability, improving accessibility, and evaluating effectiveness in larger clinical trials.

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KEYWORDS

extended reality; haptics; functional neurological disorder; biofeedback; usability; co-design; System Usability Scale

Introduction

Humans continuously learn through interactions with their environment via a perception-action cycle—a feedback loop where sensory input informs actions and the consequences of these actions (shaped by rewards and penalties) reinforce or modify behavior over time. This adaptive learning process is crucial for navigating social and environmental contexts, allowing individuals to align their behaviors with societal norms and expectations. However, maladaptive learning can occur when responses to rewards and penalties lead to dysfunctional behavior patterns, diminishing an individual's sense of agency and resulting in disordered actions [1]. We hypothesize that functional neurological disorder (FND) may arise from such maladaptive learning within the perception-action cycle, where certain reinforced behaviors disrupt normal functional responses, contributing to symptoms and reduced voluntary control over bodily actions.

FND is a complex, debilitating condition with symptoms comparable in severity and societal cost to those of epilepsy or multiple sclerosis [2]. FND encompasses several subtypes—functional seizures, functional movement disorders, persistent perceptual postural dizziness, and functional cognitive disorder—stemming from interplay between neurological and psychological mechanisms [3]. Yet, only about 50% of United Kingdom health boards have established care pathways for FND, underscoring significant gaps in treatment [4]. Recent advancements in neurotechnology and better understanding of FND pathophysiology have revealed shared mechanisms (such as abnormal sensorimotor processing and disruptions in sense of agency) that can be targeted by novel therapeutic strategies [3]. Notably, extended reality (XR) approaches have been proposed within a stepped-care rehabilitation framework [5], enabling interventions to be tailored based on symptom severity and delivered from clinic to home settings. XR is an umbrella term encompassing immersive technologies that blend digital and physical environments, including augmented reality (AR), virtual reality (VR), and mixed reality (MR). AR overlays digital information onto the real world, VR fully immerses users in a computer-generated environment, and MR allows interactive overlay of artificial elements onto the real world. XR platforms can incorporate haptic (touch-based) feedback and guided suggestions to engage patients through bottom-up sensory input and top-down cognitive cues, respectively, aiming to retrain the disrupted perception-action links underlying FND symptoms [6]. For example, haptic feedback may provide real-time physical cues to encourage movement, while positive verbal reinforcement ("You're doing great!") can facilitate operant conditioning during VR rehabilitation [7].

A survey of 527 individuals revealed high comorbidity rates among patients with FND, with pain (78.1%), fatigue (78.0%), and sleep disturbances (46.7%) being the most common symptoms, often worsening postdiagnosis [8]. Effective FND management underscores the need for transparent diagnosis explanations to improve patient understanding and enable personalized treatment strategies [9]. The National Institute of Mental Health's Research Domain Criteria framework [10] offers a dimensional perspective for understanding FND [11], guiding the development of neurotechnologies and biomarkers to better categorize its heterogeneity. The recent proposal for the inclusion of the sensorimotor domain in the Research Domain Criteria highlights the growing recognition of sensorimotor processing in mental health [10], presenting opportunities for intervention through XR neurotechnologies.

Building on previous VR-based interventions [12], we proposed the integration of haptic feedback into an XR setting to modulate the balance between sensory attenuation and amplification using an operant conditioning framework [7]. Haptic feedback in visuo-motor tasks plays a crucial role in reinforcing the perception-action cycle, primarily through efference copy and corollary discharge integration, which differs from motor imagery-based VR training [13]. The efference copy is an internal duplicate of motor commands from the supplementary motor complex [14], allowing the cerebellum and sensory areas to predict sensory consequences of movement [15]. This predictive function enables the brain to distinguish between self-generated actions and external stimuli, an essential aspect of sensorimotor learning. When haptic feedback is absent, motor learning relies on mental simulations without new sensory data, potentially reinforcing maladaptive internal models, as observed in cerebellar dysfunction [13,16]. In adaptive XR learning, haptic feedback serves as real-world sensory input, aiding in the recalibration of maladaptive internal models and reducing overreliance on predictive mechanisms associated with mental simulations in VR-only settings. Studies show that without haptic input, individuals struggle to correct motor prediction errors, as their internal model fails to recalibrate effectively [17]. By integrating haptic feedback into XR rehabilitation, we aim to recalibrate maladaptive sensorimotor patterns related to fatigue (effort-reward mismatch [18]), pain, weakness, dystonia, and seizures.

Support for XR-based functional motor disorder (FMD) rehabilitation also stems from intentional binding research, which suggests that repeated operant experiences enhance implicit agency by reinforcing associative learning [19]. This highlights the distinction between explicit and implicit agency: explicit agency, tied to conscious awareness, can be strengthened through demonstrations like Hoover's sign or tremor entrainment [20], while implicit agency is shaped through repeated operant conditioning [7]. These mechanisms interact via top-down and bottom-up pathways, which can be experimentally modulated in XR through exafference—the controlled simulation of external stimuli. However, the ethical, cost, and usability concerns associated with digital health interventions necessitate stakeholder engagement to ensure alignment with broader health care goals. Industry-driven digital health innovation plays a key role in assessing how these technologies impact health care systems and patient outcomes. Our research focuses on evaluating the usability of an XR neurotechnology platform for biofeedback training in functional limb weakness, combining

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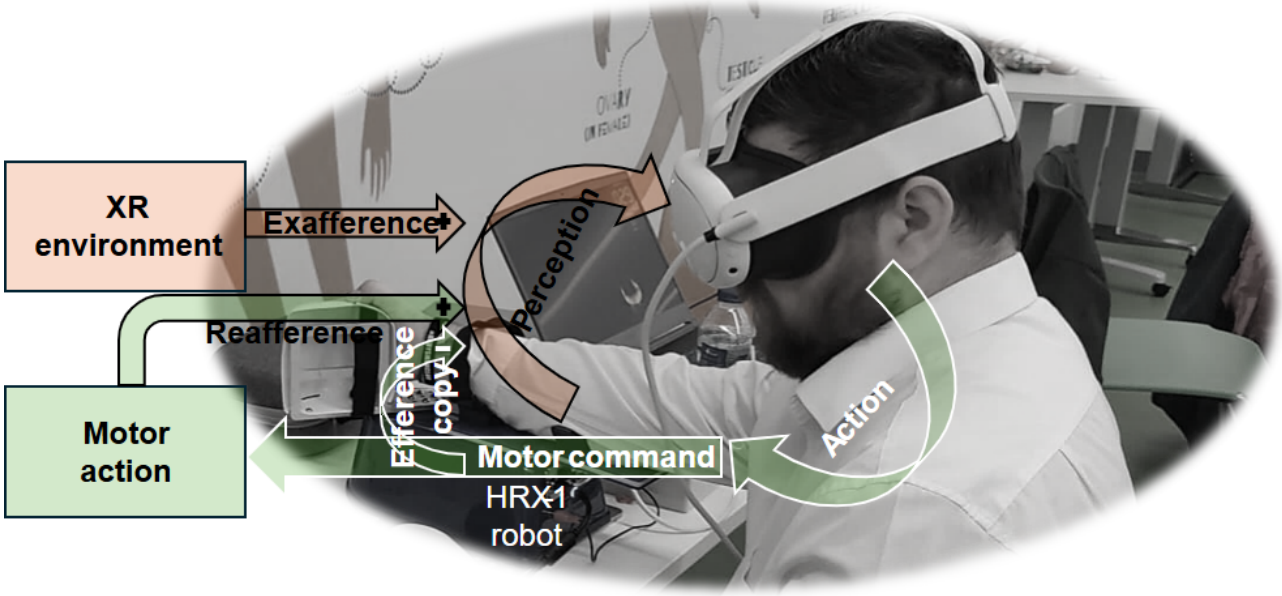
bottom-up haptic feedback with top-down visuo-motor task suggestions (refer to Figure 1) [6]. The ultimate goal is to develop precise, technically effective, sustainable, and patient-friendly XR neurotechnologies for FND rehabilitation. Industry-driven innovation plays a key role in translating these technologies into practice by evaluating their impact on health care systems and outcomes. The ultimate objective is to ensure that such neurotechnology is not only effective but also user-friendly, acceptable, and accessible for people with FND. In this context, this study adopted a coproduction approach to co-design an XR biofeedback training platform for functional limb weakness in FND and to assess its usability with end-users.

Figure 1. Perception-action coupling for extended reality (XR) biofeedback training to modulate bottom-up reafference with exafference through a haptic robot (HRX-1) to support movement in cases of functional weakness. Top-down modulation is influenced by guided visual and verbal suggestions presented via XR feedback. A distinction can be made between efference copy—internal brain duplicates of motor commands (in action)—and corollary discharge, which involves expected sensory signals due to those motor commands (in perception).



Methods

Study Setting and Participants

This study consisted of two phases: an exploratory survey (Delphi method) conducted online to inform platform design and a subsequent in-person co-design workshop for usability evaluation.

In phase 1, an exploratory Delphi survey was conducted online, where a convenience sampling method was used to recruit individuals with lived experience of FND as “experts by experience” from the United Kingdom Royal Preston Hospital’s FND service team’s networks led by the PPIE (Patient and Public Involvement and Engagement) leads. In total, 20 individuals (experts by experience) with FND participated in the initial round of the Delphi survey. Participants provided feedback via an online questionnaire. The survey collected both quantitative and qualitative data on several topics: familiarity with VR and haptic technologies, perceptions of comfort and ease of use, anticipated relevance and impact of an XR-based therapy for FND, and potential barriers to adoption (such as, cost, access to equipment, technical support, and side effects). Responses were analyzed to extract common themes and requirements that the PPIE lead presented at the National Rehabilitation Centre (NRC) Rehabilitation Technologies Conference 2024 [21] (NRC Rehabilitation Technologies Conference 2024 poster and slides in Multimedia Appendix 1). Based on the survey findings, we codeveloped with the PPIE leads and industry partners (Human Robotix Ltd and Nudge Reality Ltd) a prototype XR neurotechnology platform. We selected the Human Robotix HRX-1 upper-limb haptic system (a portable robotic device providing force feedback) and Nudge Reality’s “Hoop Hustle” XR game as the core components for our platform, as these were judged by the PPIE leads to best meet the identified needs (detailed specifications of the hardware and game options are available in Multimedia Appendix 2). The HRX-1 device can assist or resist arm movements with precise torque control, while Hoop Hustle is a VR game that can be adapted for therapeutic exercises.

For the phase 2 co-design and usability testing workshop, a purposive sampling approach was used to recruit participants specifically from the United Kingdom Royal Preston Hospital’s FND Service team, including PPIE leads. We then conducted an in-person workshop involving 6 participants drawn from the FND service community: 3 FND patient representatives (1 female and 2 male) and 3 health care professionals (2 physiotherapists and 1 neurologist; 2 female and 1 male). All 6 participants are coauthors of this paper for the participatory design approach. Before the workshop, participants provided informed consent. The session took place in a rehabilitation clinic setting and lasted about half a day.

Ethical Considerations

As this work was part of a patient engagement and technology co-design project, it was conducted with institutional review board notification but was determined to be a service development and quality improvement activity not requiring full National Health Service (NHS) Research Ethics Committee

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review. All participants gave written informed consent for their involvement and for publication of deidentified feedback. The study was carried out in accordance with the Declaration of Helsinki principles of ethical research.

Procedure and XR Platform Tasks

Given the selection of Human Robotix's HRX-1 system for upper limb rehabilitation (Human Robotix's HRX-1 system in Multimedia Appendix 3) and Nudge Reality's "Hoop Hustle" game (Nudge Reality's XR games in Multimedia Appendix 4) by PPIE leads, efforts were focused on adapting these technologies to test 3 conditions: VR relaxation, XR positional feedback, and XR force feedback. During the co-design workshop, the prototype XR platform was introduced, and participants were guided through 3 interactive training tasks, each representing a different mode of biofeedback.

Experimental Robotic System

A 1-degree-of-freedom HRX-1 desktop robot (refer to Figure 2) equipped with a direct-drive electromagnetic motor for wrist flexion or extension movement was used in the study. The robot offers high flexion or extension torque (up to 2 Nm), position and torque sensing, and a variety of control modes in a compact robotic platform. The design of the HRX-1 robot is substantially more compact and lighter than existing comparable systems to enable easy transportation and installation for the studies in clinical, research, and at-home environments. The safety of the robot operation was implemented at mechanical (range of motion limitation with end-stops), electric (limitation for the maximal electric current), and software (limitation on the maximal speed of movement) levels. Previously, robots have been successfully used in clinical and research studies [22-24]. In this study, the HRX-1 robot was integrated with VR tasks.

Figure 2. HRX-1 robot that can generate programmable wrist flexion and extension torques for assistance or resistance during the experimental study.

VR Relaxation Task

Participants wore a Meta Quest 3 VR headset to experience a guided relaxation session. The VR environment featured calming scenery (eg, a gradually descending landscape or serene nature scene), accompanied by a gentle narrative instructing the user in relaxation techniques (for instance, breathing exercises, and progressive muscle relaxation cues). The purpose of this task was to familiarize users with VR and induce relaxation, which can help reduce FND symptom intensity. Participants remained seated during this task. Notably, based on user feedback from the Delphi survey, we avoided any instructions that would conflict with VR immersion (as one Delphi respondent cautioned that this could cause disorientation). The task lasted about 5 - 7 minutes.

XR Position Feedback Game (Hoop Hustle)

In this task, participants engaged with hoop hustle, a therapeutic game developed for XR rehabilitation. The user's goal in the game is to move their affected arm (or a controller held in that arm) to "shoot" balls in VR through a series of hoops or targets at varying positions. The game provides real-time visual

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feedback on the accuracy and speed of the user's arm movements. For example, when a participant moves their arm, a corresponding arm or cursor in VR is shown, allowing them to adjust their movement to align with the hoop. Successful hits (getting the ball through the hoop) trigger immediate positive feedback (visual effects and encouraging sounds). The game's difficulty can be adjusted—for example, hoop height and size can be modified to accommodate the user's range of motion, and the speed of ball generation can be tuned. During the workshop, an operator adjusted these settings as needed to ensure each participant could comfortably attempt the task. This task emphasized positional biofeedback (augmented visual feedback of movement) without additional force resistance. Each participant practiced for several minutes until they felt they had experienced the core mechanics of the game.

XR Force Feedback Task

The HRX-1 haptic robot was integrated with the hoop hustle game to provide force feedback during the exercise. Participants grasped the end-effector of the HRX-1 device, which was programmed to apply gentle resistive forces or assistance during specific arm movements in the VR game. For instance, as a participant guided a ball toward a hoop in VR, the device might add a slight downward resistance, requiring the user to exert additional effort and thus engage proprioceptive feedback pathways. In this way, the XR force feedback task combined visual and haptic biofeedback. We also implemented a simple exercise game: the wrist handle of the robot was used to control a visual cursor shown in the screen, and a participant's task was to rotate the handle with their wrist follow a pseudo-random movement of a target on the screen as accurate and as fast as possible, similar to the tasks used in [25]. A participant could observe the progress task on the screen (visual modality) and feel the assistive and resistive wrist flexion or extension torques generated by the robot (force feedback modality). This was included to explore how force feedback might help reveal or train aspects of motor control in FND (eg, addressing sensory attenuation deficits). Each participant spent around 5 minutes with force feedback enabled. One participant with functional dystonia required a brief rest during this task due to muscle fatigue; however, all participants were able to attempt the task to some extent.

Throughout the session, participants were encouraged to "think aloud" and share any difficulties or observations (eg, if the headset felt uncomfortable or if a task was confusing). A facilitator took notes on these observations to supplement the formal feedback.

Data Collection and Analysis

After completing all 3 tasks, participants filled out the system usability scale (SUS) questionnaire for each task. The SUS is a 10-item questionnaire yielding a score from 0 to 100, where higher scores indicate better perceived usability. We chose the SUS because it is a well-established, quick tool for usability assessment, suitable even for small samples [26]. Participants also provided written free-text feedback on their experience with each task and the overall platform. These responses were collected on paper forms and later transcribed. In addition, the workshop concluded with a short group discussion, allowing participants to collectively reflect on what aspects of the platform worked well and what improvements they would prioritize. The discussion was later summarized in notes.

Quantitative data from the SUS were summarized using descriptive statistics, given the small sample size. We report individual SUS scores per participant and per task, as well as the range and median for each task's scores. Following convention [27], we interpret SUS scores using an adjective rating scale for context: scores above~85 are considered "excellent," around 70 - 85 "good,"~50 - 69 "okay," and below 50 "poor" in terms of usability perception. We did not perform inferential statistical tests due to the exploratory nature of this pilot and the limited number of subjects. Qualitative data (written feedback and facilitator notes) were analyzed thematically. Two researchers (1 patient representative and 1 study investigator) independently reviewed the feedback to identify recurring themes. Using NVivo 12 (QSR International), feedback comments were coded with initial labels corresponding to aspects of user experience (eg, "hardware discomfort," "audio feedback," and "game difficulty"). These codes were then grouped into higher-level themes through discussion and consensus. Representative participant quotes were extracted to illustrate each theme in the Results.

Results

Phase 1: Exploratory Delphi Survey Report (CHERRIES Checklist)

We present the results from our first round of the Delphi survey according to the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) [28], aimed at the translation of the VR haptics technology for biofeedback training in FND. The survey gathered online feedback from 20 (N=20) individuals with lived experience of FND, considered experts by experience for technology translation.

Design

This was an online Delphi survey aimed at gathering high-level user requirements for the development of a VR haptics biofeedback training platform for FND rehabilitation.

The survey sought to assess perceptions and expectations of VR and haptic biofeedback technology for rehabilitation, potential benefits and usability considerations for upper and lower limb motor retraining, and barriers to adoption and accessibility concerns among individuals with lived experience of FND.

Development and Pretesting

Survey Development

The survey was co-designed by a multidisciplinary team (co-authors of this report), including clinicians, researchers, industry partners, and FND patient representatives. It was pilot-tested with a small group of patients with FND and clinicians to refine clarity, content, and usability.

Survey Refinements

Feedback from pilot testing led to revisions in question phrasing, response categories, and survey logic. Adjustments were made

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to ensure accessibility for individuals with neurological impairments (eg, clear navigation and avoiding long response formats).

Recruitment Process and Sample Characteristics

Target Population

The survey targeted adults (≥18 y) with FND, particularly those experiencing functional limb weakness.

Recruitment Strategy

Participants were recruited through FND patient advocacy organizations (eg, FND Hope, FND Action). Neurology clinics specializing in FND care. Online FND support groups and social media communities. The survey link was shared via email, social media, and organizational websites.

Participation Details

Participation details included a survey link access, in which an open-access URL was provided with IP duplicate detection enabled. No monetary incentives were provided; participants were thanked for their contributions in follow-up communications.

Survey Administration

The survey was hosted on a General Data Protection Regulation (GDPR)-compliant, secure online platform (MS Forms is part of Microsoft 365, which adheres to GDPR, Health Insurance Portability and Accountability Act (HIPAA), and ISO 27001 security standards).

Response Tracking

Anonymous participation was allowed; no email registration was required, and no IP tracking or cookies were used.

Survey Content

The question structure of the survey included a combination of question types, as listed in Textbox 1.

Textbox 1. Question structure of the survey.

- Demographics (age, gender, FND diagnosis history, and previous XR or VR experience).
- Experience with VR or haptic technology (previous use in gaming, therapy, etc).
- Perceived benefits of XR biofeedback (customizability, real-time feedback, and usability).
- Barriers to adoption (cost, accessibility, and concerns about motion sickness).
- Open-ended qualitative feedback (expectations, concerns, and usability considerations).

Data Handling and Statistical Analysis

Data Privacy Measures

No personally identifiable information was collected. Responses were stored in a secure, encrypted database, accessible only to authorized researchers.

Analysis Methods

Descriptive statistics were used for Likert-scale responses (percentages and means). Qualitative thematic analysis was performed using NVivo for open-ended responses.

Results Reporting

Response Rate

Response rates are described in Textbox 2.

Textbox 2. Response rate.

- Total respondents: 20.
- Completion rate: 85% (17 fully completed responses).
- Dropout rate: 15% (3 partial responses).

Key Findings

Key findings are mentioned in Textbox 3.

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Textbox 3. Key findings.

- Participant demographics:
  - Peak age group: 35-44 years.
- Gender: predominantly female.
- Experience and perception of VR and haptic technology
  - Awareness of VR technology: high, but varied levels of familiarity.
  - Haptic technology experience: less common.
- Comfort levels: mostly positive, but some concerns about mask and goggle discomfort and motion sickness.
- Perceived relevance and potential impact: high perceived relevance for FND rehabilitation.
- Participants prioritized:
  - Customizable exercises.
  - Real-time biofeedback.
  - Immersive environments.
- Barriers and challenges identified
  - Accessibility concerns: (1) cost of VR equipment, (2) availability through NHS or insurance coverage, (3) WiFi or connectivity limitations.
- Usability issues:
  - Motion sickness concerns.
  - Need for guidance on using XR biofeedback at home.
- Potential safety concerns:
  - Risk of falls or overstimulation.

Discussion of Bias and Limitations

Potential Biases

The two types of potential biases are (1) selection bias: participants were self-selected, possibly favoring tech-savvy individuals, or those already engaged in FND support groups; and (2) response bias: some participants may have been overly optimistic or cautious in their feedback.

Limitations

This study has two limitations. The first is the small sample size (N=20); the results are preliminary and not generalizable to all patients with FND. The second is the use of the single-round Delphi survey; the findings require further validation through additional rounds or larger-scale studies.

Conclusion

The first round of the Delphi survey provided key insights into the usability, expectations, and barriers associated with XR haptics biofeedback training for FND rehabilitation.

Key Takeaways

Participants perceived high potential benefits but highlighted cost, accessibility, and usability concerns. There was a strong interest in real-time feedback and customization to tailor the technology to individual needs. Concerns about motion sickness, equipment comfort, and NHS availability need to be addressed for successful adoption.

Future Steps

Refining usability features based on patient feedback in phase 2 co-design and usability testing. Further stakeholder engagement with clinicians, patient organizations, and industry partners in phase 2 co-design and usability testing. Scaling the study to validate findings with a larger sample and additional Delphi rounds following in phase 2 co-design and usability testing.

Phase 2: Usability Scores (Quantitative Results)

Basic usability testing typically benefits from the purposive selection of 5‑10 participants [29]. Here, all 6 workshop participants completed the XR position feedback and XR force feedback tasks, and 5 completed the VR relaxation task (1 health care professional was unable to try the VR relaxation due to time constraints). Table 1 presents the SUS scores given by each participant for each task. Overall, the XR position feedback game received the highest ratings with a median score of 91.3, and all participants rated it above 70. The VR relaxation task had a bimodal distribution of scores—2 participants rated it very highly (~88‑90) while 3 participants gave it scores below 50, indicating poor usability for those individuals. The XR force feedback task had generally positive scores from 4 participants

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(range, 80.0 - 95.0), but 1 participant (Participant 3) gave a very low score (27.5). According to Bangor et al's [27] adjective rating scale for SUS, the low scores in the 40s for the VR relaxation task correspond to a "poor" usability experience, despite the same task being rated as "excellent" by others. Similarly, the force feedback task's scores suggest mostly "good" to "excellent" usability, with one clear outlier in the "poor" range. In contrast, the XR position feedback task's scores correspond to "good" or "excellent" usability across all users. These results highlight a high degree of variability in user experience for the more complex or condition-sensitive tasks (VR relaxation and force feedback), compared to the consistently positive experience with the position feedback game (XR system usability testing script and XR system usability testing results in Multimedia Appendices 5-8).

Table . The system usability scale (SUS) score was calculated for each participant across extended reality (XR) tasks, including virtual reality (VR) relaxation, XR position feedback control, and XR force feedback control. Participant 6 did not participate in the VR relaxation task.

	XR force feedback SUS	XR position feedback SUS	VR relaxation SUS
Participant 1	80.0	95.0	47.5
Participant 2	62.5	72.5	90.0
Participant 3	27.5	92.5	45.0
Participant 4	82.5	100.0	87.5
Participant 5	95.0	90.0	45.0
Participant 6	87.5	85.0	__[a]

[a]not available.

Phase 2: User Feedback and Thematic Analysis (Qualitative Results)

Qualitative analysis of the feedback revealed several key themes regarding the user experience and suggestions for improvement. Participants provided free-text responses regarding their VR relaxation task experience, which were analyzed for future technology improvement.

Immersion and Visual Artifacts (Improve Realism and Reduce Pixelation)

Some participants struggled with visual quality, stating that the graphics were "bland" and "pixelated." One participant mentioned, "The environment didn't feel real enough to help me relax."

Discomfort With the Headset (Select Lighter Weight Hardware)

Participants found the VR headset too heavy, making it difficult to use for prolonged relaxation. One user commented, "The headset was too bulky—it distracted me rather than helping me relax."

Voice Guidance Issues (Offer Customizable Audio Settings)

While some users appreciated the guided relaxation, others found the voiceover distracting or repetitive. One participant stated, "The voice instructions were too constant—I wanted more silence to focus on breathing."

Motion Sickness and Unpleasant Sensations (XR May Minimize Some Disorienting Effects)

A few participants experienced dizziness, with one stating, "The moving visuals made me feel nauseous, which completely defeated the point of relaxing." This suggests a need for less intense motion effects.

Mixed User Feedback on Effectiveness (Offer Alternatives, Eg, Audio-Only Modes)

Some participants felt the VR relaxation could be beneficial if improved, while others stated they would prefer alternative relaxation methods (eg, audio-only relaxation without VR).

Participants also provided free-text responses regarding their experience with the XR position feedback task, which were analyzed for future technology improvement.

Real-Time Visual Feedback Issues (Lower Latency Motion Tracking)

Some participants struggled with feedback clarity, reporting inconsistencies in motion tracking. One participant noted, "Sometimes my arm was perfectly aligned, but it wouldn't register the movement."

Difficulty in Adjusting Position (Online Recalibration)

A few participants found it difficult to match their movements with the system's feedback. One participant commented, "I kept missing the hoop even when I thought I was on target." Another commented, "I liked that it gave immediate feedback, but sometimes I didn't understand what I did wrong." This suggests that target alignment and hit detection need refinement.

Engagement and Gamification Elements (Expand Game-Like Elements)

Some participants enjoyed the interactive aspect of the task. One participant stated, "It was fun trying to score points, but I wish there were more levels or challenges."

Physical Strain Concerns (Individualized Task Intensity)

A small number of participants reported discomfort or strain during prolonged use. One participant mentioned, "I could feel my arm getting tired quickly—I think the tracking required more effort than I expected."

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Mixed User Feedback on Usability (Lower Latency Motion Tracking and Online Recalibration)

Some participants felt that improving the accuracy and responsiveness of the tracking would make the task more engaging. One participant suggested, “If it was more precise in detecting movements, I’d find it much more enjoyable.”

Participants provided additional free-text comments about their experience using the XR force feedback task, which were analyzed for future technology improvement.

Lack of Personalization (Individualized and Adaptive Resistance)

Several participants noted that the resistance levels were not well-adjusted to their needs. One participant stated, “The force applied felt either too weak or too strong—there was no in-between.” This suggests a need for adaptive resistance control.

Discomfort and Fatigue (Improve Ergonomics)

The heaviness of the headset and the effort required to overcome force resistance were cited as major concerns. One participant reported, “After a few minutes, my arm felt very fatigued, which made the task frustrating rather than helpful.” Another stated, “The device felt restrictive rather than supportive.”

Low Engagement (Expand Game-Like Elements)

The lack of an interactive or gamified element was also highlighted. One participant commented, “There’s no motivation to keep going—it’s just moving against resistance with no real feedback.”

Potential for Improvement (Future Potential)

Some participants saw promise in the concept but suggested improvements, such as, “It would help if the system guided me on whether I was applying the right force,” “Maybe add vibration or a sound effect when I get the force correct,” and “If the resistance could change based on how strong I am, that would be much better.”

Summary

In summary, the qualitative feedback provided actionable information that complemented the SUS usability scores. It explains why certain tasks received lower scores (eg, VR relaxation’s technical and content issues leading to poor ratings from half the group) and reinforces the need for customization in the force feedback task (given one user’s difficulties). The participatory nature of the co-design and usability testing session ensured that end-user voices directly informed the next steps of platform refinement.

Discussion

Principal Results

This study is, to our knowledge, the first mixed methods evaluation of an XR-based biofeedback training platform co-designed for individuals with motor FND. Through a 2-phase coproduction approach, we obtained rich stakeholder input and preliminary evidence of usability. Our key finding is that the XR position feedback game was the most well-received component of the platform, with consistently high SUS usability scores and positive feedback from users. This task, dubbed “Hoop Hustle” in the prototype, required participants to perform wrist movements to control a VR interface with accompanying visual feedback. The strong performance of this task suggests that combining visual feedback in an intuitive pointing game can be highly engaging and easy to use for people with functional weakness. Participants likely benefited from the clear, immediate cause-and-effect in this game, which may have contributed to a sense of accomplishment and control.

In contrast, the VR relaxation module yielded a polarized reaction: some individuals felt deeply relaxed and enjoyed the experience (reflected in very high SUS scores), while others struggled with aspects of the VR environment (leading to poor usability ratings). These divergent outcomes highlight that a one-size-fits-all relaxation experience may not suit everyone; factors such as susceptibility to motion sickness, comfort with wearing a VR headset, and personal preference for meditation-style activities can greatly influence one’s experience. The XR force feedback task showed intermediate and more variable usability. Most participants handled the force-feedback task moderately well (SUS~80‑95 for 4 participants), indicating that they understood the task and could perform it, but one participant (P3) had an extremely negative experience (SUS 27.5). P3’s case is particularly informative: this participant has functional dystonia (a subtype of FND causing involuntary muscle contractions), which likely made it difficult to perform the steady force output required by the task. This resulted in frustration or fatigue, as reflected in both the low usability rating and the participant’s comments describing the force task as “hard to manage” and “tiring.” This finding underscores that individual clinical differences (such as the type of motor symptoms) can dramatically affect the usability of specific training tasks. Notably, the same participant (P3) rated the XR position task very highly (92.5), much higher than they rated the other 2 tasks. We interpret this to mean that while the force feedback task was not well-tolerated by P3, the position feedback game was accessible and enjoyable even for someone with dystonia. It is possible that the position task’s design—emphasizing range of motion and coordination rather than sustained force—was better aligned with this participant’s abilities. This suggests a need for personalized task selection or customization: users might benefit from having multiple training task options and skipping or modifying those that aggravate their symptoms.

Across all tasks, the qualitative feedback provided further insight into these quantitative results. For instance, participants who gave lower SUS scores often cited specific issues that explained their discomfort. Those who rated the VR relaxation poorly mentioned problems like visual graininess and a sense of disorientation when the virtual scene “breaks” (one user described a loss of immersion at a certain transition, eg, reaching a virtual staircase where the illusion was not convincing). On the other hand, participants who enjoyed the relaxation task commented on feeling calm and appreciating the break from active gameplay, which may reflect personal differences in how individuals prefer to engage (active interaction vs passive relaxation). Similarly, mixed feedback on the force task

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corresponded with whether users felt the haptic feedback was appropriate; some found it novel and motivating, while others found it confusing or difficult to calibrate their strength. We can summarize the qualitative feedback themes as follows.

Hardware Comfort and Ergonomics

Multiple participants commented on the VR headset's weight and fit. One noted that the "headset is heavy" and that the straps were "a bit fiddly" to adjust properly. Another participant suggested the need for a more personalized or lightweight headset, saying they "would prefer [their] own personal headset" if using the system regularly. These comments indicate that physical comfort is a crucial factor, as discomfort could limit how long users with FND (who may have neck or upper body weakness) can wear the device. Ensuring a better fit and lighter hardware in future versions was a unanimous priority among participants.

Immersiveness and Visual or Auditory Feedback

Participants generally appreciated the concept of the immersive training tasks, but they pointed out specific issues that broke their sense of immersion. For instance, one participant observed that in the VR relaxation, "the picture quality is bland" (low resolution), which detracted from the experience. Visual artifacts or graphics glitches were noticed by another, who commented that such issues "break immersion." On the auditory side, a few participants felt the guided meditation voice-over in the VR relaxation was "too artificial" and constant, making it "distracting" rather than soothing. One user recommended incorporating periods of silence or softer, nonverbal audio, noting that "Constant speech is too much–needs time to breathe." In the XR game, participants enjoyed the sound effects, but one suggested adding more varied sound cues for feedback (eg, different sounds when a hoop is scored versus missed). Enhancing the realism and quality of sensory feedback (both visual and auditory) would likely improve user engagement.

Task Difficulty and Personalization

There was a strong consensus on the importance of adjusting the tasks to individual capabilities. In the hoop hustle game, participants had different skill levels; 1 patient with a more severe weakness struggled initially, so the facilitator enlarged the hoop and reduced the required movement range. This kind of on-the-fly personalization was appreciated. Participants explicitly mentioned features they would like to see: "adjustable height [of hoops]" and "hoop size" options, as well as the ability to slow down or speed up the game pace. In the force feedback task, the participant with dystonia noted that the resistance made the task quite challenging for them, but felt it might be helpful if it could be tuned to their strength level. Across the feedback, "personalization" emerged as a key theme–one size does not fit all in this diverse group. Future versions of the platform should include user-specific calibration, difficulty settings, and possibly adaptive algorithms that modify task parameters in real-time based on performance.

Perceived Benefits and Engagement

Despite the critiques, most participants expressed enthusiasm for the platform's concept. Several referred to the approach as a "brilliant idea" and were eager to see it refined. They reported finding the interactive game enjoyable–one health care professional noted that the competitive element of trying to get the ball through the hoop "made it fun, so you forget you're exercising." Participants also believed the platform could increase patient motivation to perform rehabilitation exercises, as it "doesn't feel like therapy" in the traditional sense. The relaxation task was seen as potentially useful for calming down patients before or after physical exercises, although it clearly needs improvement to be effective for everyone.

Practical Considerations (Accessibility)

Echoing the Delphi survey results, workshop participants raised practical questions. They debated whether the system would be used in clinics or at home. For home use, participants stressed the need for proper guidance and support: "If this was sent to patients, there would need to be a help guide or 24/7 tech support," one participant said, concerned about less tech-savvy users. The idea of a shared device versus personal ownership was discussed; some felt a single headset could be used by multiple patients in a clinic if properly sanitized, while others thought long-term users would benefit from having their own device configured to their needs. Concerns about cost were mentioned again; one participant estimated "it's [£]1000… (US $1330) I could not afford [this]" and hoped it would be provided through the NHS or insurance. These discussions highlight that for the platform to be implementable, issues of cost, training, and technical support must be addressed alongside its technical development.

These thematic insights demonstrate the value of a mixed methods approach: the quantitative data identified where usability was strong or weak, and the qualitative data helped explain why those outcomes occurred. Crucially, the workshop confirmed that co-design is not only feasible but beneficial in developing neurotechnology for FND. Participants' real-time feedback led us to identify specific improvements (eg, modifying the VR content and adding adjustable settings in the game) that we might not have fully appreciated without their involvement. The inclusion of both patients and clinicians ensured that the usability assessment considered practical use in a clinical context.

Comparison with Previous Work

Our findings align with existing literature emphasizing user-centered design for health technologies. Previous studies have noted that even small samples (5 - 10 users) can uncover the majority of usability issues in a system [29]. In our case, 6 users were sufficient to highlight distinct strengths and weaknesses of the platform. The variability in VR relaxation feedback is reminiscent of observations in broader VR applications: while VR can provide immersive therapeutic experiences, factors like motion sickness and comfort remain challenges to address. The need for personalization in rehabilitation technology is well-documented; for instance, usability studies of other rehab games have found that adaptive difficulty can significantly improve user engagement and outcomes. Our results specifically extend this understanding to FND, suggesting that personalization may not only improve engagement but might be necessary to accommodate neurological symptoms like dystonia or fatigue. From a

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neurological perspective, the concept of using haptic feedback and VR to retrain the perception-action cycle in FND draws on theories of sensory attenuation and agency in functional movement disorders. By providing congruent visual and haptic inputs corresponding to the user's intended movements, the platform aims to reinforce the association between effort and sensory feedback, potentially strengthening the efference copy mechanism that is hypothesized to be underactive in patients with FND [14,30,31]. While our study did not directly measure clinical outcomes or neurophysiological changes, the positive usability of the position and force feedback tasks is a critical first step toward implementing such therapeutic concepts in practice. A recent review by [12] also emphasized VR's promise for addressing mechanisms of agency and attention in FND; our practical findings complement this by showing that patients are willing to engage with VR or haptic systems, provided they are comfortable and accessible.

Limitations

This study has several limitations. First, the sample size was small (5 - 6 participants for usability testing), and all participants were from a single clinical center and also coauthors, which could introduce some bias or limit critical feedback. The findings should be interpreted as preliminary and exploratory; a larger, independent sample will be needed to validate and generalize the usability results. Second, participants' familiarity with XR technology varied, and those with previous VR or gaming experience might have found the system easier to use, potentially influencing their SUS scores. We did not formally quantify each participant's XR technology background, which is a confounding factor that future studies should measure. Third, we focused on 3 specific XR tasks (VR relaxation, XR position feedback, and XR force feedback). Other functionalities (eg, bilateral training or cognitive tasks in XR) were not included and could present additional usability challenges or benefits not captured here. Fourth, the reliance on subjective SUS scores introduces potential bias, as individual expectations or novelty effects can influence ratings. We mitigated this by collecting detailed qualitative feedback, but objective performance metrics were not analyzed in this pilot. Fifth, as an initial co-design and usability study, we did not assess clinical efficacy, for instance, whether using the platform yields improvements in motor function or FND symptoms. Such outcomes will need evaluation in subsequent trials. Finally, our personalization of the tasks was done manually by the facilitators rather than through built-in adaptive algorithms. This limits the consistency of the user experience; an automated personalization mechanism would be ideal to ensure each user gets an optimally challenging experience. Despite these limitations, the study provides valuable insights into the user experience of an XR neurotechnology platform tailored for FND. To our knowledge, this is one of the first studies to report detailed usability data for an XR haptics platform in FND rehabilitation. The co-design approach proved effective in identifying user priorities and potential pitfalls early in the development process.

Future Directions

The next steps following this study will address the identified issues and test the platform on a broader scale at home [32]. FMD involves involuntary-feeling but voluntary-appearing movements, linked to a disrupted sense of agency due to impaired sensory attenuation, that is, the brain's predictive suppression of self-generated sensory feedback [33]. This impairment, involving brain regions like the primary motor cortex, cerebellum, and right temporo-parietal junction, leads to difficulties in distinguishing self-initiated actions from external stimuli [34]. Conversely, sensory amplification, mediated by the posterior parietal cortex, heightens sensory perception through attention. XR presents therapeutic potential by balancing sensory attenuation and amplification [6]. VR allows controlled manipulation of predictive coding, helping recalibrate agency and sensory processing in FMD. The comparator model (refer to Figure 3) suggests that agency arises when predicted sensory outcomes align with actual feedback, which can be reinforced through haptic feedback in XR. Here, linking active inference in motor control lies in its ability to explain and address motor dysfunctions [35]. By recognizing that the brain updates perceptions and modifies actions to minimize prediction errors, this framework offers insights into abnormal motor control, where disrupted sensory prediction leads to impaired agency and movement errors. In rehabilitation, this perspective supports the development of XR biofeedback interventions, where haptic and visual feedback can help recalibrate faulty sensorimotor predictions. By reinforcing accurate sensory-motor associations, these technologies may restore agency and improve motor function, offering a novel, personalized approach to therapy. Indeed, XR technologies have been shown to enhance sensorimotor processing, but usability for patients with FMD must be assessed. Early user involvement, particularly in conditions like functional dystonia, is critical to refining XR rehabilitation design. Our study engaged stakeholders from academia, industry, and health care (NHS, England) to classify technological needs into incremental or revolutionary advancements. Notably, no commercial or research-based XR biofeedback systems currently exist specifically for FMD rehabilitation.

In response to user feedback, we are working with the developers to improve the VR relaxation module (enhancing graphics, refining the audio guidance, and possibly adding options for different scenes or background music) [32]. We are also implementing in-software settings that allow end-users or therapists to easily adjust game difficulty, visual or auditory feedback levels, and force feedback intensity. In addition, we plan to incorporate a brief calibration or tutorial at the start of a session, where the system can gauge a user's comfortable range of motion and strength, and automatically set initial task parameters accordingly. These changes aim to embed personalization directly into the platform. A follow-up study is being designed to involve a larger cohort of patients with FND in a multisession at-home trial with the refined platform [32]. That study will evaluate not just usability, but also short-term effects on motor function and symptoms, using clinical scales and objective performance metrics within the game. We will also examine learning effects–whether repeated use leads to improved user proficiency or changes in feedback preferences–to understand how usability evolves over time. An important future direction is to explore remote or home usability of this platform [32]. Given the interest in home-based rehabilitation (and lessons

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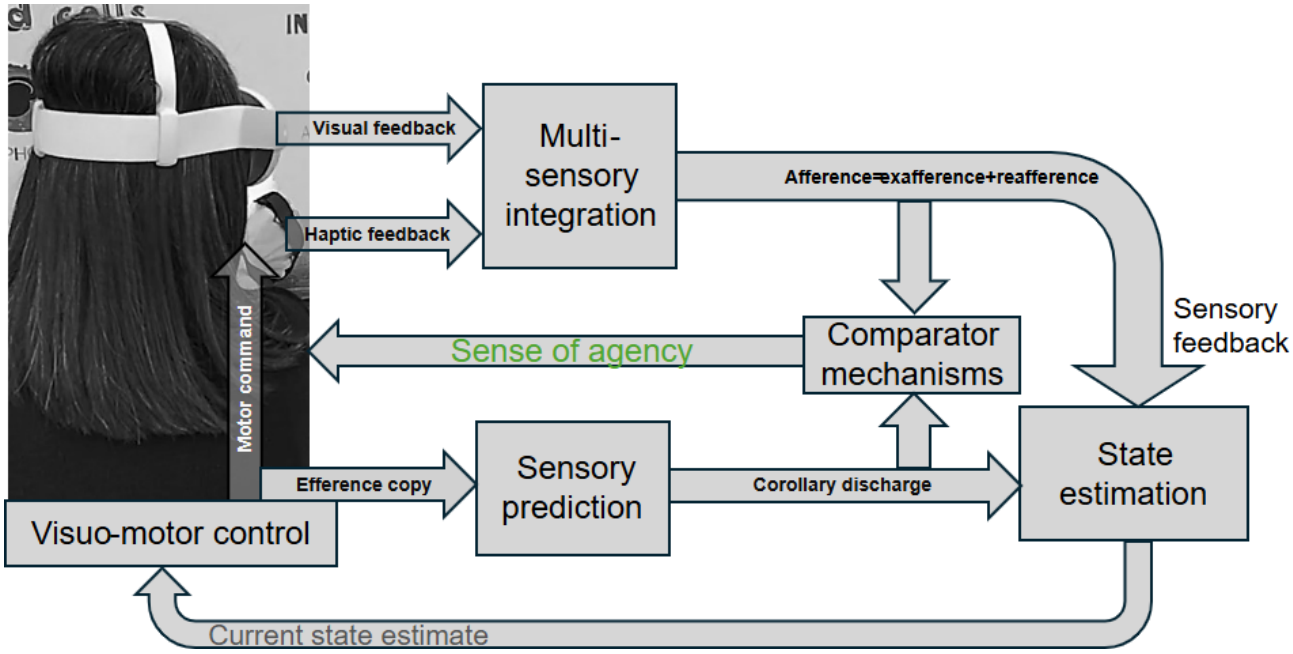
learned during the COVID-19 pandemic), we aim to test whether patients can effectively use the XR system at home with minimal supervision. This will involve developing comprehensive user guides, integrating remote monitoring capabilities (so therapists can track usage and progress), and ensuring robust technical support is available. Addressing these factors will be essential for translating this coproduced XR platform into a scalable, real-world therapeutic option for individuals with FND.

Figure 3. Based on the comparator model, when a motor command is issued, an accompanying efference copy is generated, which allows the brain to predict the expected sensory outcome of the action. This predicted outcome is then compared to the actual sensory feedback upon action completion. A strong the feeling of agency is experienced if there is a close match between predicted (corollary discharge) and actual sensory information (afference) from the environment. This comparator model can also explain feeling of agency in virtual extended reality (XR) environments where a virtual representation mimics the user's physical movement, providing exafference that, when combined with reafference, provides users the sense of agency (feeling of agency).



Conclusions

Through a collaborative coproduction approach, we developed and pilot-tested a novel XR (VR+ haptic) biofeedback training platform for patients with functional upper limb weakness due to FND. Our usability findings are encouraging: an interactive XR position feedback game was rated highly usable by all participants, and a VR relaxation experience received very positive feedback from some users. At the same time, the variability in responses, particularly the challenges faced by one participant during the force feedback task, highlights the necessity of a flexible, user-tailored design in such neurotechnologies. One-size-fits-all solutions are unlikely to succeed in the FND population given the diversity of symptoms and user preferences. By systematically incorporating user feedback, we identified concrete areas for improvement (such as hardware comfort and software adaptability) that will guide the next iteration of the platform. This study demonstrates that patients with FND and clinicians are not only capable of providing meaningful input into technology design but are eager to do so when the goal is to enhance therapy. With further refinement and larger-scale testing, the XR platform has the potential to become a valuable tool in FND rehabilitation, offering engaging, at-home training that reinforces patients' agency and motor function in a way that is enjoyable and customized to their needs.

Acknowledgments

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Authors' Contributions

Dutta A was responsible for conceptualization, lead funding acquisition, lead methodology development, visualization, original draft writing, and contributed equally to project administration and supervision. LR, KH, and MN contributed equally to data curation and investigation. LL, JT, and Das A also contributed equally to the investigation. AB, IF, and Das A provided supporting roles in funding acquisition and methodology. JT led in providing resources, with AB and IF offering supporting contributions. Das A performed validation and contributed equally with Dutta A to project administration and supervision. For writing—review and editing, Dutta A took the lead, with supporting contributions from Das A, AB, IF, and JT.

Conflicts of Interest

AB is the CEO of Nudge Reality Ltd., and IF is the CEO of Human Robotix Ltd. Both provided technology and expertise for this project. Their involvement was limited to technical development, and they were not involved in the analysis of usability data. The other authors declare no competing interests.

Multimedia Appendix 1
NRC Rehabilitation Technologies Conference 2024 poster.
[PDF File, 2895 KB - xr_v2i1e68580_app1.pdf]

Multimedia Appendix 2
NRC Rehabilitation Technologies Conference 2024 slides.
[PDF File, 928 KB - xr_v2i1e68580_app2.pdf]

Multimedia Appendix 3
Human Robotix's HRX-1 system.
[PDF File, 655 KB - xr_v2i1e68580_app3.pdf]

Multimedia Appendix 4
Nudge Reality's XR games.
[PDF File, 131 KB - xr_v2i1e68580_app4.pdf]

Multimedia Appendix 5
XR System Usability testing script.
[PDF File, 42 KB - xr_v2i1e68580_app5.pdf]

Multimedia Appendix 6
XR System Usability testing results – Force Feedback.
[ZIP File, 12330 KB - xr_v2i1e68580_app6.zip]

Multimedia Appendix 7
XR System Usability testing results – PositionFeedback.
[ZIP File, 12241 KB - xr_v2i1e68580_app7.zip]

Multimedia Appendix 8
XR System Usability testing results – Relaxation.
[ZIP File, 10073 KB - xr_v2i1e68580_app8.zip]

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Abbreviations

FMD: functional motor disorder
FND: functional neurological disorder
GDPR: General Data Protection Regulation
HIPAA: Health Insurance Portability and Accountability Act
HRX-1: human robotix system
MR: mixed reality
NHS: National Health Service
NRC: National Rehabilitation Centre
PPIE: Patient and Public Involvement and Engagement
SUS: system usability scale
VR: virtual reality
XR: extended reality

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Augmented Reality Framework to Measure and Analyze Eye–Hand Coordination in Stroke Patients with Unilateral Neglect: Proof-of-Concept Study

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Abstract

Background: Stroke is a leading cause of disability, often accompanied by unilateral spatial neglect (USN), which severely impairs recovery. Traditional assessments like paper-pencil tests provide limited insights into behaviors and eye–hand coordination during real-world tasks. Advances in hand pose estimation and eye tracking in combination with augmented reality (AR) offer potential for data-driven assessments of naturalistic interactions.

Objective: This proof-of-concept study presents and evaluates a multimodal behavioral tracking system that captures gaze, body, and hand movements during interactions within an AR environment. Our primary goals are to (1) validate that this system can achieve robust and accurate interaction data capture in clinical settings, (2) show that the system can reliably detect known USN behavioral patterns, and (3) explore how comprehensive data can provide new understanding of eye–hand coordination deficits in USN.

Methods: We developed an AR-based assessment system using Microsoft HoloLens 2 and an external body-tracking camera to capture real-time gaze, hand, and body movements in an interactive environment. Multimodal data streams were temporally synchronized, fused, and filtered to enhance spatial accuracy and availability. Tracking performance was benchmarked against a traditional optical motion-capture system to validate reliability. In a study, 7 patients with right-brain lesions with mild to moderate USN and 8 healthy controls participated. Each performed a designed reaching task, stamping virtual sheets of paper that appeared randomly on a table. We analyzed participants' search behavior patterns to assess attentional biases and examined gaze anchoring timing during targeted reaching motions to explore potential eye–hand coordination deficits.

Results: The fusion of hand-tracking data from the HoloLens 2 and external system reduced tracking loss from 25.7% to 2.4%, with an absolute trajectory error of 3.27 cm. The system demonstrated high usability and was well accepted by patients. Data from the control group confirmed the absence of intrinsic lateral biases in the system and task design. The USN group displayed typical search behavior through ipsilesional biases in gaze direction during visual exploration (median deviation 7.46 [1.61-9.48] deg, $P<.05$) and longer times to find contralesional targets (median difference 1.08 [0.20-1.80] s, $P=.02$). Additionally, the eye–hand coordination analysis revealed lateral differences in gaze anchoring during targeted reaching motions in the USN group, with earlier fixation on contralesional targets (median difference 112 [71-146] ms, $P=.02$).

Conclusions: The proposed AR framework provides a novel, comprehensive data-driven method for capturing interaction behavior in a controlled, yet naturalistic environment. Our results demonstrated the system's effectiveness in measuring hallmark USN symptoms, such as gaze and head orientation biases, and highlighted its potential to complement traditional assessments by offering deep insights into torso rotation and eye–hand coordination with a high resolution and accuracy. This data-driven approach shows promise for enhancing current USN assessment practices and gaining new insights into patients' behaviors.

(JMIR XR Spatial Comput 2025;2:e70985) doi:10.2196/70985

KEYWORDS

visual neglect; stroke rehabilitation; augmented reality; eye-hand coordination; gaze anchoring; hand tracking; eye tracking; digital twin; motion capture; neurorehabilitation technology; unilateral spatial neglect; AR

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Introduction

Stroke represents a profound public health challenge, affecting one in four adults during their lifetimes [1]. Of the numerous poststroke impairments, unilateral spatial neglect (USN) is a particularly significant barrier to patient recovery: Evident in up to 43% of patients after a right-hemispherical brain lesion (RBL) [2], this condition is characterized by a reduced ability to attend to contralesional stimuli, impacting essential daily activities [3,4]. Consequently, the rehabilitation journey is fraught with challenges, including heightened fall risks, poorer rehabilitation outcomes, extended hospitalization time, and reduced likelihood of being discharged home [5-7].

In 75% of USN cases, patients present with egocentric visual USN [8], marked by a bias of visual exploration through head and eye movements toward the ipsilesional side [9]. However, USN is a heterogeneous condition, encompassing a spectrum of attentional deficits across visual, tactile, auditory, and proprioceptive domains [10-12]. Consequently, multiple tests are typically employed to measure the severity of USN. Paper-pencil tests such as the Bells/Stars Cancelation [13] and Line Bisection [14] are commonly used due to their good sensitivity among paper-pencil assessments [15]. However, discrepancies between test results and patients' real-world behavior are frequently reported [16].

Behavioral assessments like the Catherine Bergego Scale address this gap by evaluating neglect during several activities of daily life, but they require labor-intensive direct observation and offer limited quantitative insight into task execution [17]. Technological approaches, such as gaze analysis during free visual exploration, provide quantitative insights but are restricted to specific test settings [18]. Evidence suggests that attentional biases in USN extend beyond eye movements, being influenced by motor acts and proprioceptive feedback. For instance, the orientation of the trunk mid-sagittal plane was shown to modulate the perceived forward direction and shift neglected space [19-22]. Moreover, proprioceptive cues, such as pointing, guide the direction of visual attention [23]. Accordingly, patients with USN exhibited biases of visual attention toward the ipsilesional sides of these cues [24].

These findings highlight the need for a comprehensive behavioral tracking system that can capture eye, body, and hand movements during task execution in environments that closely mimic real-world conditions.

Virtual reality (VR) or augmented reality (AR) systems that are able to track gaze and hand movements partially address these requirements. VR has been explored to simulate real-world interactions for studying USN [25]. However, immersive VR introduces new challenges such as user disconnection from the real environment, proprioceptive disconnection (eg, the inability to see one's own hands), and motion sickness [26]. By contrast, AR overlays simulated elements onto the real world, creating a mixed reality experience, addressing aforementioned discomforts [26] and integrating both physical and virtual objects into experiments. Consequently, AR has recently seen a growing application in neuroscience and rehabilitation [27,28].

However, despite these advantages, standalone AR systems still fall short of the comprehensive behavioral tracking requirements identified earlier. The inside-out tracking approach of typical AR systems like the Microsoft HoloLens 2 (where sensors on the headset track the environment) provides limited full-body tracking beyond hands and head position. Additionally, hand tracking can fail when users' hands are not positioned directly in front of them or during complex object interactions.

To address this gap, researchers have begun complementing inside-out tracking with external motion capture (Mocap) systems [29,30]. In clinical settings, external tracking systems combined with AR have primarily been used to position virtual objects relative to physical ones, particularly for surgical guidance applications [31,32]. However, there is limited evidence of this combination being utilized to capture comprehensive behavioral data in clinical rehabilitation contexts [33].

Accordingly, we propose a novel framework encompassing a head-mounted AR system (HoloLens 2, Microsoft USA [34]) and a single RGB-D camera (ZED 2i, Stereolabs USA), providing the following:

- A controlled environment allowing for a wide range of user interactions with both digital and real-world elements.
- Accurate tracking of gaze orientation, hand movements, and body posture during task execution, with improved hand-tracking accuracy and availability enabled by sensor fusion.
- Detailed digital reconstruction of interactions to enable comprehensive behavioral analysis.
- Automated data integration and metric extraction to enable quantitative analysis, with a focus on eye–hand coordination.

The goal of this proof-of-concept study is to demonstrate the feasibility and utility of our tracking framework through a systematic validation approach. Our validation encompasses both a technical accuracy assessment against a marker-based VICON system and clinical validation through the detection of known USN symptoms. Beyond confirming that the framework captures established USN behavioral patterns, we explore lateral differences in eye–hand coordination during goal-directed actions as a novel behavioral marker. With this, our framework shows promise in enhancing current USN assessment practices and gaining new insights into patients' behaviors.

Methods

System Overview

The system (Figure 1) comprised three main parts. (1) A tracking system, which measures and records gaze direction, hand, and body movements. It enables interactions with (2) a simulated virtual environment, which is overlaid onto the real world using a head-mounted AR display. (3) An offline data-processing and data-reconstruction system creates a digital twin of the captured interactions, allowing for in-depth analysis.

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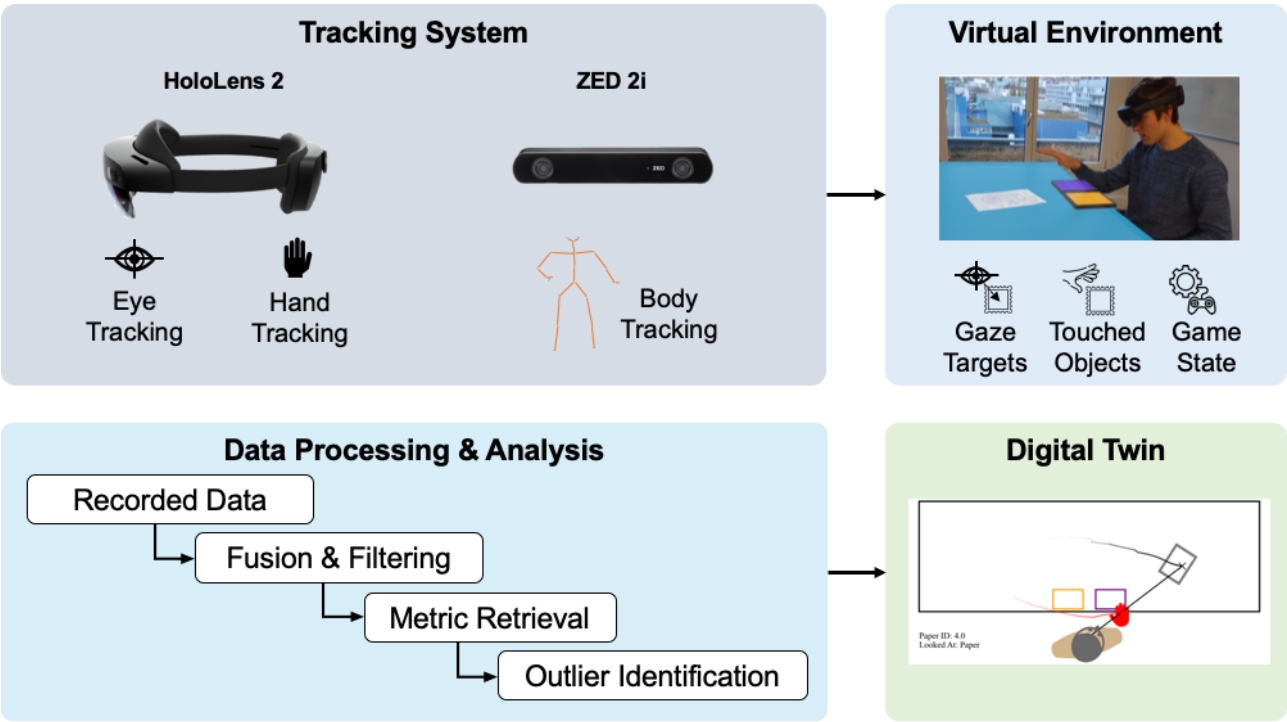
Figure 1. Overview of the system.



Tracking System

We obtained interaction data from multiple sources. The HoloLens 2 provided gaze and hand-tracking data through the Mixed Reality Toolkit API [35]. These data were recorded alongside the state of the virtual environment, at a frequency of 40 Hz, capturing the users' view at each moment. Additionally, an external RGB-D camera (ZED 2i, Stereolabs, USA) was set up in front of the users, facing them.

The coordinate frame was aligned to that of the HoloLens during setup by taking a picture of a checkerboard with both cameras and extracting the relative transformation between the two. Using the manufacturer-provided body-tracking algorithms [36], body key points were extracted, including hand and shoulder joint positions. This pose information was recorded at a frequency of 30 Hz. The hand-tracking data were additionally streamed in real time to the HoloLens to complement the on-device hand tracking that was at times subject to tracking loss.

Virtual Environment Design

The virtual environment was designed to assess the hand- and eye-tracking capabilities of our system, specifically its ability to capture metrics relevant to USN. To encourage naturalistic behavior, it was structured as a game around a familiar, easy-to-learn task that required repeated, precise reaching motions: stamping virtual sheets of paper. For this task, users sat in front of a physical table overlaid with a holographic table. Two virtual ink pads, one orange and one violet, were shown to participants, positioned as shown in Figure 2. During the task, virtual sheets of paper appeared sequentially in a random order across 21 locations distributed radially (Figure 2). Each sheet displayed a hand outline, color-coded in orange or violet. The users selected the color by putting their hand into the corresponding virtual ink pad in front of them. They then performed a reaching motion to stamp the paper, after which it disappeared, and a new one appeared. Participants were told that their main goal was to perform this task as fast as possible, but to ensure goal-oriented reaching and precise movements toward the targets, they were also told to stamp the papers as precisely as possible within the respective hand outline.

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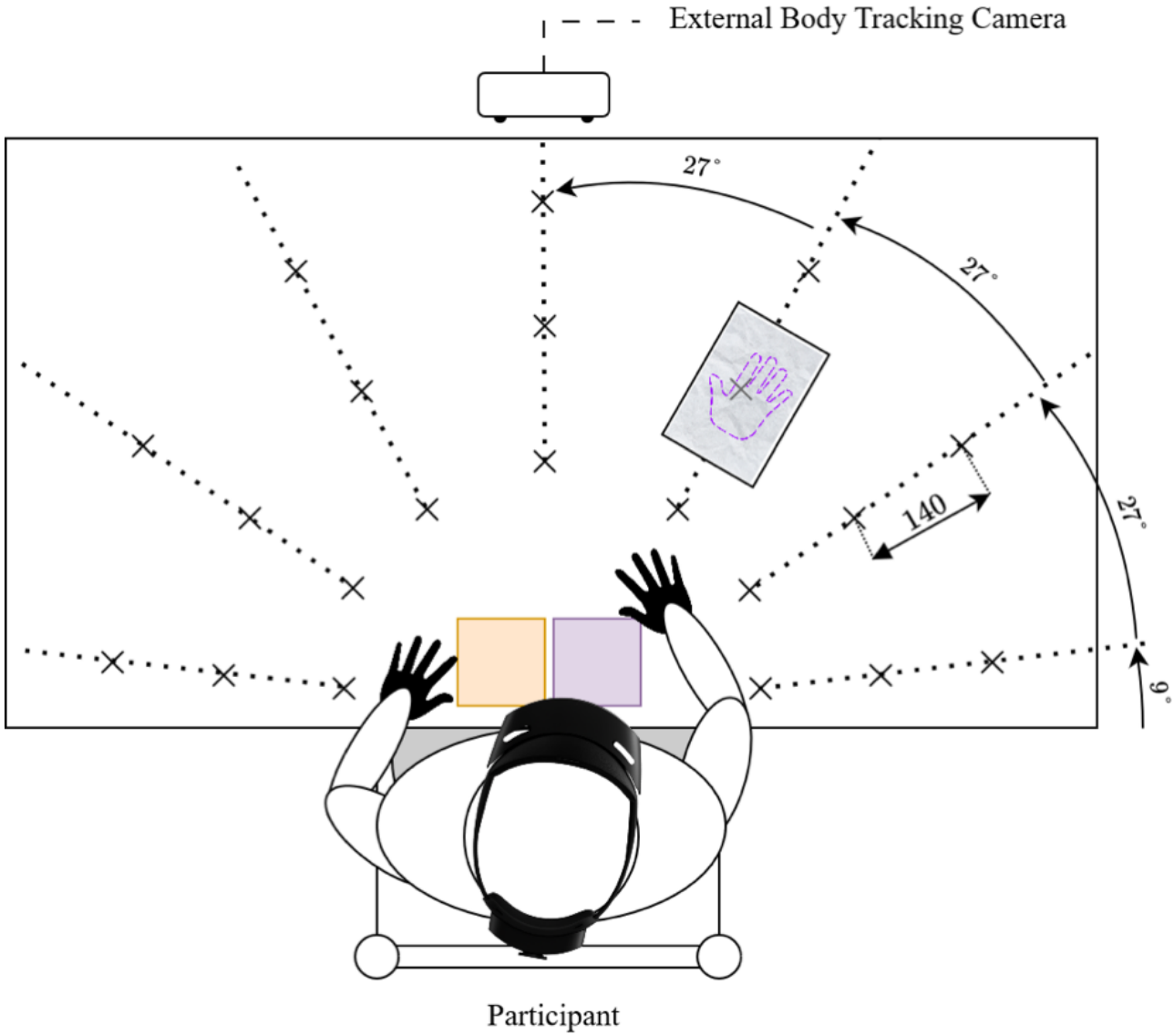
Figure 2. Top-down view of the game setup. Virtual sheets of paper appear in 21 possible locations indicated by X, radially distributed and spaced at 140 mm by default. Two virtual stamp pads are always shown in front of the user. The ZED camera for external body tracking is set up opposite of the user with a view of the entire table and the user's pose. Image of HoloLens 2 from [34].



To promote naturalistic behavior while ensuring data comparability, implicit constraints were implemented. A brief, randomized delay of 1 to 3 s after each paper was stamped encouraged users to reset their posture between trials. Moreover, the virtual sheets never appeared adjacent to each other, that is, as direct neighbors in any direction, to minimize carryover effects from the previous location. By requiring ink selection prior to stamping, each movement began from a central position and interactions followed a consistent sequence: locating the paper, selecting the ink, and finally stamping. These constraints ensured the independence and comparability of each episode without explicitly directing user actions.

An initial tutorial was introduced to help participants understand the game and the interaction with the system. This allowed users to familiarize themselves with the task and the limited field of view of the HoloLens 2, which required them to turn their heads to see all possible paper positions on the table. To ensure that all sheets were comfortably reachable, the experimenter could adjust distances between papers during the tutorial so that even the farthest sheet remained within arm's reach. This setting was kept constant during the experiment.

The repeatability of each experiment was ensured by fixing the seeds on the random number generators. Moreover, potential biases were avoided by balancing out the color of the outline on the paper, ensuring that both colors occurred equally often within and between the left- and right-hand sides of the user.

The stamping task allowed users to interact with a physical surface that aligned with the virtual one, providing direct haptic feedback. This design choice was informed by insights from pilot experiments and previous work within our research group, highlighting the importance of tactile interaction [37].

To enhance engagement, a non-directional "bling" sound, similar to a phone notification, signaled the appearance of each new paper, while a chime rewarded users when they correctly stamped a sheet. Additionally, if a user could not find the paper within ten seconds, the system automatically advanced, causing the current sheet to disappear and the next one to appear.

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Data Processing

For comprehensive behavioral analysis, accurate hand movement, gaze, and body position tracking were required. To address temporal and spatial misalignment, sensor noise, and data loss, the recorded data underwent extensive processing outlined in this section.

Temporal misalignment between the external tracking and the HoloLens 2 was corrected in two steps. During the recording, the hand poses were streamed to the HoloLens. An initial time offset estimate was obtained from the difference in sender and receiver timestamps. However, this still included network and processing delays and an error introduced by the difference in sampling rate (40 Hz vs 30 Hz). The time offset was therefore refined by maximizing cross-correlation of the normalized hand positions from both sources. Across all recordings, the cross-correlation of hand poses was on average 0.96, with external tracking data arriving with an average delay of 92 ms.

To address tracking losses and noise from either source, hand-tracking data from both the HoloLens 2 and external system were fused using a Kalman filter with a standard constant acceleration motion model. The two coordinate systems were initially aligned using a checkerboard calibration, but residual spatial errors were addressed by estimating a 3D offset within the filter. To avoid introducing temporal delays, Kalman smoothing was applied with a backward pass over the time series to achieve zero-phase filtering [38]. The filter parameters were tuned based on expected hand motion characteristics and system accuracies (Table 1). Innovation gating was used to reject outlier measurements that fell outside the 90% confidence region based on the calculated Mahalanobis distance.

Table . Kalman filter parameters.

Parameter	Value	Description
Process noise (acceleration)	3 m/s²	Expected SD of hand acceleration
Process noise (spatial offset)	0.0001 m/s	Random walk SD for coordinate alignment
External tracking measurement noise	0.02 m	SD of external tracking poses
HoloLens measurement noise	0.01 m	SD of HoloLens poses
Innovation gate threshold	90%	Confidence region for outlier rejection

Gaze data was recorded in two ways: On one hand, the gaze direction and origin were recorded, from which the construction of a gaze ray was possible. On the other hand, the intersections of the gaze ray with objects in the scene, for example, “Paper, Table, Ink Pad,” were computed at each update, and the target of the gaze was recorded. Given the reported variance of 1.5° to 3° in HoloLens 2 gaze directions [39], temporal filtering was applied to both time series. For the gaze target-object filtering, only Papers and Ink Pads were considered as targets of interest. A median filter over seven samples (spanning 0.175 s at 40 Hz) was applied to the time series. As a result, a target was considered fixated when first intersected, if subsequently the gaze remained on it for at least 50% of the sliding window duration (~0.085 s). The gaze origin and gaze direction vectors were filtered with a median filter with a 0.35 s window.

Head poses were obtained directly from the HoloLens 2 without filtering, as it exhibited little noise due to the device’s built-in robust localization system.

The torso rotation was reconstructed from the tracked chest, left, and right shoulder joints of the external tracking data. Outliers were removed based on sanity checks, asserting that the head position was always between the two tracked shoulder joints.

Metric Extraction and Data Visualization

To validate the system’s capability to measure common neglect symptoms, we focused on metrics that evaluate search behavior and attentional shifts therein. Our analysis incorporated spatial orientation metrics during the search phase (from paper appearance until target identification): average gaze direction, head rotation, and torso rotation, all computed relative to the table coordinate system using filtered sensor data and estimated forward vectors from the processed data.

For eye–hand coordination analysis, we examined the temporal relationship between gaze anchoring and motion onset. While gaze timing could be directly extracted from the gaze–target time series, determining precise motion onset required a more sophisticated approach.

An initial estimate, given by the recorded time the hand left the ink pad, was refined by identifying the optimal velocity minimum from candidate minima within the movement window. The selection was based on a multifactor scoring system that weighted (1) spatial proximity to the ink pad position, (2) hand velocity magnitude, (3) directional alignment with the target movement vector, and (4) temporal consistency with stamping events. The candidate with the lowest combined score was selected as the movement onset point.

Despite this sophisticated approach, various technical and environmental factors could still affect motion onset detection accuracy, creating the need for a systematic data quality review. To address this, we implemented an automated outlier detection system that flagged an episode for review in case the duration of the motion exceeded 1.5 times the interquartile range (IQR) beyond the upper or lower quartile for individual user measurements (accrued metric over all episodes for that user).

Other metrics, such as the time it took to find a paper after its first appearance, were also processed by this system to detect anomalies resulting from technical issues such as occasional failures to register fixations or interactions.

To facilitate the review of these episodes and, in a broader sense, enable the qualitative analysis of the recorded interactions, we

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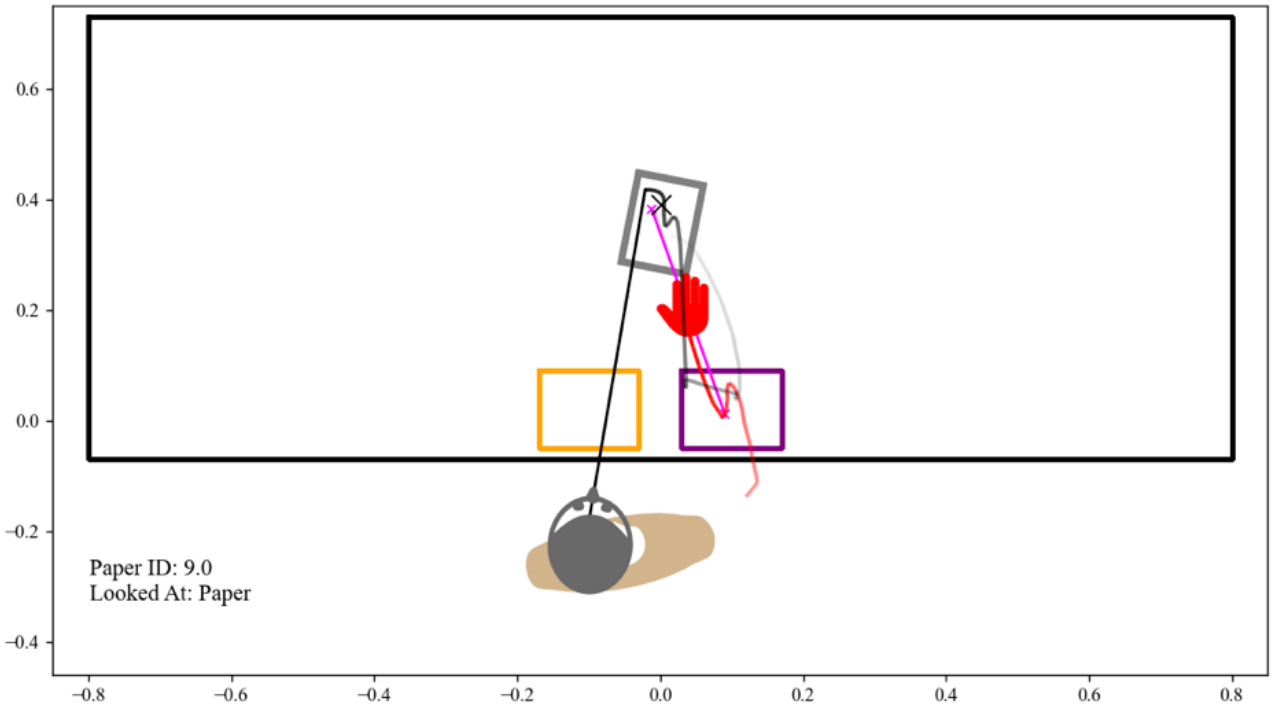
implemented a digital twin: an interactive 2D visualization tool reconstructing user interactions (Figure 3). This digital twin provided an animated top-down view of the simulated environment, displaying the users' head, torso, and hand poses, gaze directions, and hand movement data. This allowed for a visual review of the flagged episodes to determine if the anomalies resulted from technical errors rather than natural human behavior. Any episodes where the visualization revealed tracking loss during critical phases, fixation or interaction registration failures, or other clear technical errors that compromised the affected metrics were marked as outliers. These episodes were excluded from the subsequent analysis.

Figure 3. Snapshot of digital twin replay of example data from our dataset. A black X marks the current fixation point. The magenta line connects the current motion start and end point. The torso with estimated orientation is shown in brown, together with the tracked positions of the hand and head. A red path shows the hand's position history, and a black path shows the user's gaze target over the past 3 seconds, both fading with time.



The digital twin tool abstracted sensitive information, enabling secure and collaborative qualitative analysis, which both clinicians and researchers found valuable for reviewing patient behavior. Its visualization of extracted metrics provided an intuitive way to replay and contextualize gaze, motion, and compensatory strategies, making it a practical aid for identifying patterns and generating insights to guide research and rehabilitation approaches.

Tracking Accuracy Evaluation

To evaluate the hand-tracking accuracy of the HoloLens 2, the ZED 2i body tracking, and the fused hand trajectories, we compared their 3D hand positions against ground-truth data recorded at 200 Hz with a VICON motion capture system.

Participants were equipped with infrared markers placed on both shoulders, the chest, and the index knuckle of each hand. Temporal alignment of the data was achieved by maximizing cross-correlation across speed and acceleration of hand movements. All signals were resampled to a common temporal grid. The spatial alignment was initialized by finding the rigid transformation that aligned the tracked shoulder and neck positions between the systems. It was then refined via an Iterative Closest Point (ICP)-like approach, maximizing global alignment of the hand positions between the Mocap system and the filtered hand positions.

Study Design

A proof-of-concept study was conducted with patients experiencing neglect symptoms after an RBL. Each patient played three rounds of the "game," where one round consisted of one paper appearing at each of the 21 locations, for a total of 63 episodes. The first round of the game was only played with the right hand; the subsequent two rounds presented the patients with papers containing left- and right-hand outlines, requiring patients to select the correct hand for the interaction. The order in which the papers appeared, as well as their color and hand outline, was randomized across games. The randomization was balanced to obtain two right-handed interactions per paper location for a total of 42 episodes (21 episodes in the first game, 12 in the second game, and 9 in the last game). The color randomization was equally balanced, resulting in a total of 33 episodes showing purple papers and 30 episodes with orange ones.

Before the experiment was started, the participants were asked to calibrate the eye tracker of the HoloLens 2 using Microsoft's calibration tool. To complete the calibration, a Vuforia marker [40] was used to align the holographic table with the physical table.

The patients were subsequently presented with a tutorial phase, during which no data were recorded, and the sheets did not disappear. The positions of the sheets in the tutorial were the

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same as in the actual game, but the sequence and colors were different, to avoid learning effects. During this stage, the experimenter assisted patients in locating the sheets by referring to the external application monitor, which displayed the current sheet's position.

Once a participant had independently located and stamped six consecutive papers, the tutorial was terminated, and the actual assessment began. They were informed that the time was being recorded and instructed to perform the stamping task as fast and as accurately as possible.

While it was initially intended to also consider left-handed motions, we soon found that many of the patients had impairments to the contralesional limbs, which could not be attributed to USN. In the results, we therefore only considered the motion data from the right-handed interactions. For perception-only metrics, like the time until a paper was first looked at, all episodes were included in the analysis.

Ethical Considerations

The study was conducted in accordance with the latest version of the Declaration of Helsinki and received approval by the Ethics Committee of the Canton of Lucerne (ID 2017 - 02195). Before participation, all participants were informed about the content of the study, the steps and procedure of the experiment, and the goal of the study. Participants provided written informed consent and were explicitly informed of their right to revoke their consent at any time throughout the study or later. All data were anonymized to protect participants' privacy and confidentiality. Participants did not receive any compensation for their participation.

Usability

At the end of the experiment, the participants completed a usability questionnaire consisting of the following statements, each rated on a 5-point Likert scale where 1 was annotated with "strongly disagree" and 5 with "strongly agree (translated from German):

- Interacting with the elements (eg, paper, stamp) was comfortable
- I intuitively understood how to interact with the elements (paper, stamp).
- The game instructions were clear and easy to understand.
- The game maintained my attention from beginning to end.
- - I enjoyed playing the game.
- The challenges in the game were appropriate and well-balanced.
- I felt overwhelmed while playing the game.
- The game had a good pace—neither too slow nor too fast.
- I felt stressed by the game.

Results

Patient Characteristics

The study was conducted with seven right-handed patients (3 women and 4 men), between 49 and 83 years old (median 75 [58-78] y), who had an RBL. The participants were diagnosed with mild to moderate USN based on clinically relevant scores in a battery of tests (Table 2) consisting of mean gaze position (MGP) during free visual exploration (FVE) [18], bell's cancelation tests [13], and behavioral analysis using the Catherine Bergego Scale score [4,17]. While interactions with both hands were recorded, our analysis focused on the dominant and ipsilesional right hand. Only patients with little to no impairment of their right hand and arm movement were selected, which was assessed using the LIMOS score [41]. Due to time constraints, two patients (P1 and P5) completed only two out of three recordings during the experiment duration. For patient P5, this was anticipated, and they were asked to play the game with their right hand twice.

Table . USN group individual test scores on relevant clinical tests performed by clinicians prior to the study.

Patient ID	Gender	Age (y)	CBS[a]	MGP FVE[b]	CoC[c]	LIMOS[d] right hand and arm movement
P1	Female	83	4	3.92	0.04	4/5
P2	Male	49	1	1.45	0.02	5/5
P3	Male	79	0	0.43	0.15	4/5
P4	Female	77	7	3.25	0.37	5/5
P5	Male	67	5	1.33	0.09	5/5
P6	Female	74	12	2.52	0.11	5/5
P7	Male	49	0	2.00	0.09	4/5

[a]CBS: Catherine Bergego Scale (0% - 30%, higher=more neglect).

[b]MGP FVE: Mean gaze position during free exploration (cut-off>1.33°, rightward=positive).

[c]CoC: Center of cancellation (cutoff>0.081, left neglect=positive).

[d]LIMOS: 4=slowed and 5=independent.

The control group consisted of eight healthy individuals (1 female and 7 males) between 20 and 60 years old (median 31 [23-51] y). While none of the participants in the USN group had previous experience with AR devices, four out of the eight participants in the control group had previously used the technology.

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Accuracy and Availability of Hand Tracking and Torso Rotation

Hand-tracking accuracy was evaluated for the HoloLens 2 and ZED 2i tracking system individually, as well as for their fused and filtered data, using the VICON Mocap system as ground truth. For evaluation, three male users independent from the clinical study participants were chosen, and measurements were obtained from gameplay with either hand, resulting in a total of 6 recordings (3 left hand and 3 right hand). We report the tracking accuracy during the relevant dynamic reaching motion only. The results in Table 3 show that the fused approach and the HoloLens 2 standalone achieved similar hand-tracking accuracies, with root mean square errors (RMSE) of 3.27 cm and 3.54 cm, respectively. The ZED 2i data contained large outliers (52.5 cm at the 95th percentile), which increased the RMSE to 37.1 cm. The median absolute error (AE) was also larger at 5.51 cm. The HoloLens 2 had frequent tracking loss, resulting in 74.3% availability. The ZED 2i and the fusion of the two sources achieved much better rates of 97.2% and 97.6%, respectively.

Table . Tracking accuracy results versus VICON data.

Tracking method	RMSE[a] (cm)	Median AE[b] (cm)	95th percentile AE[b] (cm)	Availability[c]
HoloLens 2	3.54	2.71	6.30	74.3%
ZED 2i	37.1	5.51	52.5	97.2%
Fusion	3.27	2.24	5.80	97.6%

[a]RMSE represents the root mean square average trajectory error during the reaching motion.

[b]Median AE and 95th percentile AE show the distribution of absolute errors across all samples.

[c]Availability indicates the percentage of frames with valid tracking data.

The torso rotation extracted from the ZED2i body tracking was compared to that obtained from the VICON system and evaluated during the search phase. The median signed error was 0.26°, with a median AE of 1.45° and 97.1% availability (Table 4).

Table . Torso rotation accuracy and availability against VICON data during free visual exploration[a].

Metric	Value
Median angle error (signed)	0.26°
Median absolute angle error	1.45°
95th percentile absolute angle error	4.41°
Availability	97.1%

[a]Availability indicates the percentage of frames with valid tracking data.

Omissions

While patients received assistance and cues to search the entire space during the tutorial, no cues were provided during the actual experiment to avoid influencing search behavior. Papers that remained unfound after 10 s automatically disappeared, and the next paper appeared to maintain game progression. This time limit resulted in some omissions in the USN group: 9.3% (15/161 episodes) of papers on the left side and 3.3% (5/151 episodes) on the right side were not found within the time limit. The control group showed no omissions, nor were any omissions recorded for centrally positioned papers in either group.

Biases During Search Behavior

In line with previous research [8,9], the visual exploration of patients with USN was hypothesized to be biased toward the ipsilesional side. Using the proposed system, we analyzed the gaze direction during the search phase, as well as torso and head rotation. In the following, all statistical tests were performed using a Wilcoxon signed-rank test (due to the small number of participants) for a zero-mean hypothesis with a two-sided alternative. The level of significance was chosen at α=.05.

The results in Figure 4 show that the USN cohort exhibited a significant ipsilesional shift in the average gaze direction during FVE (median 7.46 [1.61-9.48] deg, P=.05). Similarly, a significant rightward trend of their average head rotation was observed (median 4.03 [2.52-7.94] deg, P=.03). A trend of an average torso rotation toward the contralesional side in the USN group did not achieve statistical significance (median −3.81 [−4.78 to 0.48] deg, P=.22) . In the control group, the average head orientation was shifted slightly, but significantly, toward the left during the search phase (median 1.40 [−4.25 to −0.04] deg , P=.02). Aside from that, the zero-mean hypothesis could not be rejected for the average gaze direction (median −1.75 [−2.87 to -0.10] deg, P=.11) and the average torso rotation (median 1.44 [−1.37 to 4.00] deg, P=.31) in the control group.

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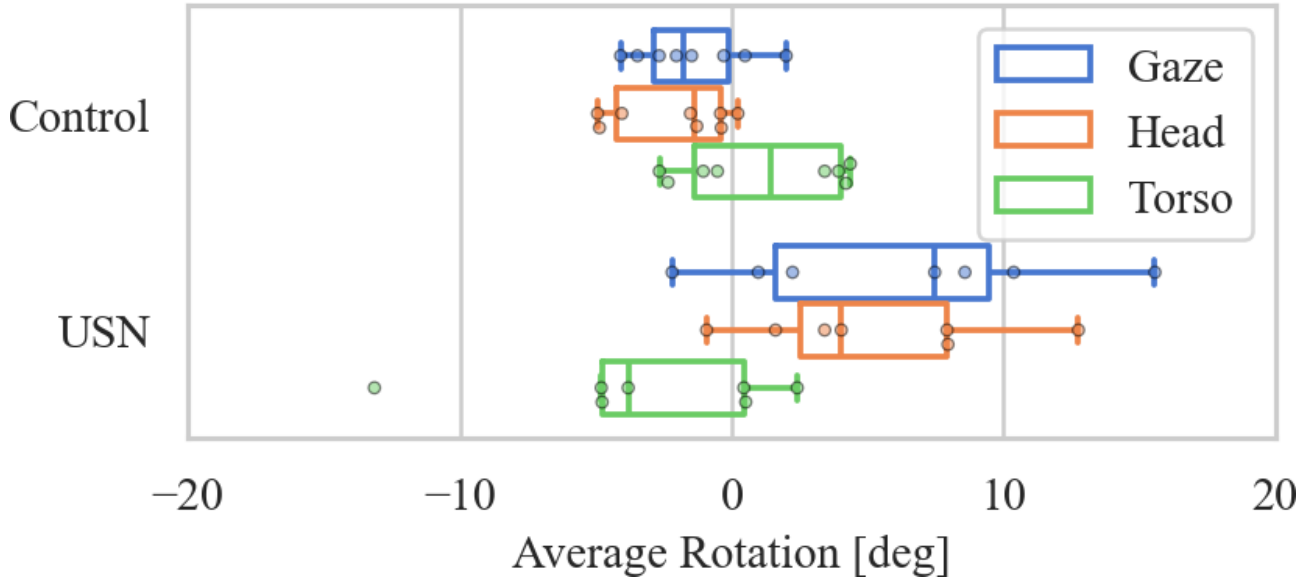
Figure 4. Boxplots and data points for average orientation of gaze, head, and torso relative to the table in front of the users. Boxes represent the IQR, the solid lines indicate the median, the whiskers indicate the minimum and maximum values that are not considered outliers.

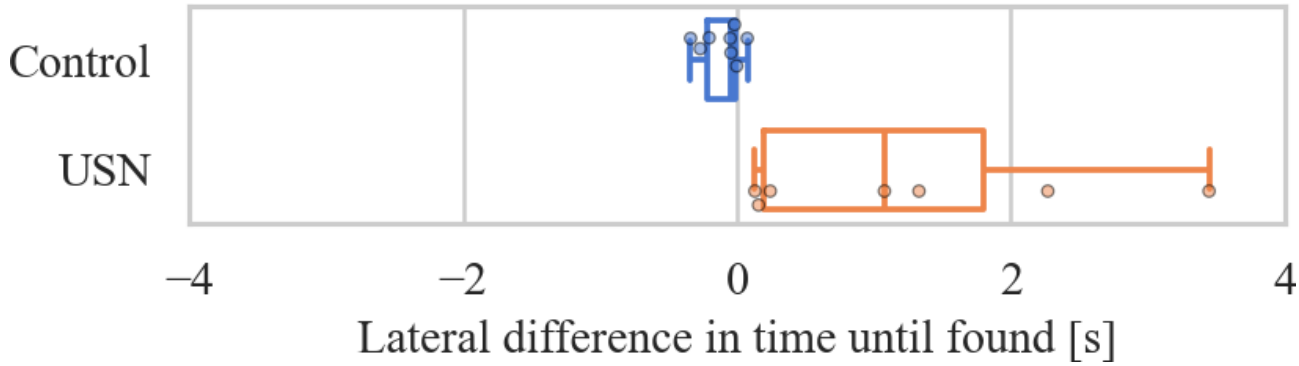


To investigate the effect of biased search behavior on the time it took users to find sheets of paper placed on the left and right sides of the table, we conducted a pairwise comparison. Each sheet on the left (within the two leftmost radial sectors) was matched with its mirrored counterpart on the right, and for each, we calculated the average time it took a user to find it across multiple trials. We then compared the average time for each paper on the left to the average time for its counterpart on the right. For example, if a user took an average of 8 s to find a specific sheet on the left and an average of 5 s to find its counterpart on the right, the difference for that pair would be +3 s.

This difference was computed for each pair and then averaged across all pairs per user to yield an overall measure of lateral difference. In the control group, out of the total 504 recorded episodes, 64 were flagged and removed as outliers (12.7%), whereas 50 of the total 399 episodes were removed in the USN group (12.5%). Any pairs with no data on either side were excluded from the analysis.

The results (Figure 5) indicate that the USN group took significantly longer to find papers on the left side compared to the right (median difference 1.08 s [0.20-1.80], P=.02), whereas no significant difference in the control group was observed.

Figure 5. Pairwise differences of the time until each paper was found on the left and right side. A positive difference indicates that the papers on the right were found sooner. Box represents the IQR, the solid line indicates the median, the whiskers indicate the minimum and maximum values that are not considered outliers. Control: n=8, median −0.05 s [−0.22 to −0.01], P=.08; USN: n=7; median 1.08 s [0.20-1.80], P=.02.



Differences in Timing of Gaze Anchoring

As an important aspect of eye–hand coordination, we investigate gaze anchoring behavior during targeted motion. A typical episode involved the following steps: (1) the participants were located and fixated on the paper; (2) gaze was shifted to the ink pad while the participant selected a color with their hand; (3) hand motion was initiated away from the ink pad toward the remembered location of the paper; and (4) gaze anchoring was shifted back to the paper to guide the ongoing motion.

Eye–hand coordination is a complex field of research. One aspect that is often considered is the timing of fixations with respect to intent and concrete actions [37]. In patients with USN, disrupted spatial attention may particularly affect this temporal coordination between gaze and movement. In the following, we therefore analyzed lateral time differences between (3) and (4). This was done using a pairwise comparison, similar to the previous section. For each side, we calculated the average time between the onset of hand movement and the fixation of the target paper, comparing these times between left- and right-hand sides. For example, if a user fixated on a sheet 100 ms after

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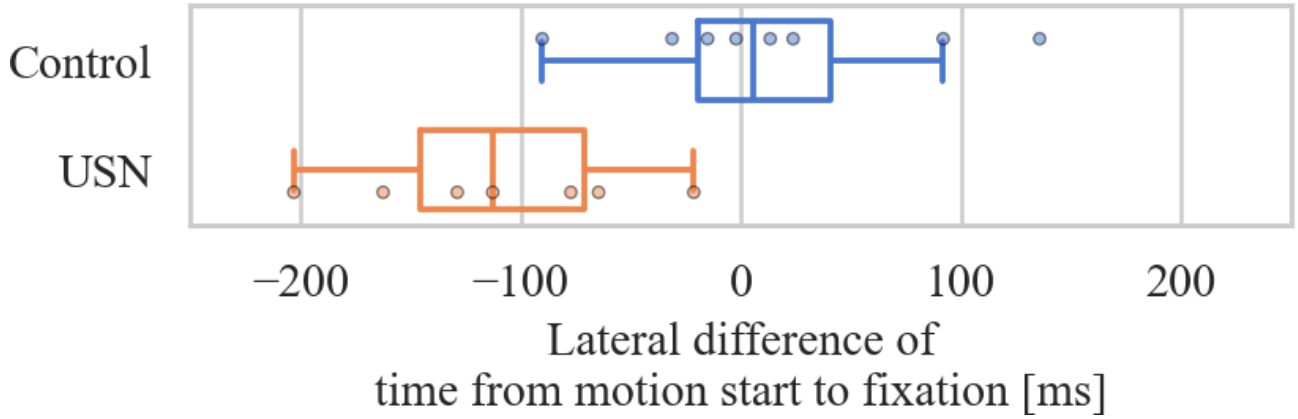
initiating hand movement toward it on the left side and 300 ms on the right, the difference for this pair would be −200 ms. The outlier review resulted in 52 of the 336 episodes with right-handed interaction data (15.5%) being rejected in the control cohort and 47 out of 246 (19.1%) in the USN group.

The results (Figure 6) show that the USN group fixated on the target of their motion significantly earlier for targets on their left compared to their right (median difference of 112 ms [-146 to -71], *P*=.02). In contrast, the control showed no significant lateral difference (*P*=.74).

Figure 6. Pairwise difference between the sheets on the left and on the right side and of the time between motion onset and fixation of the motion target. A negative difference indicates that sheets on the left were fixated earlier. The box represents the IQR, the solid line indicates the median, and the whiskers indicate the minimum and maximum values that are not considered outliers. Control: n=8, median 5 ms [-19 to 41], *P*=.74; USN: n=7, median −112 ms [-146 to -71], *P*=.02.



Given that gaze anchoring has been shown to shift in time with longer duration movements [42], we examined whether the observed laterality in gaze timing could be explained by corresponding differences in movement durations. To assess this, we analyzed the relationship between lateral differences in gaze timing and lateral differences in the duration of reaching motions across participants. Pearson correlation analysis revealed a moderate correlation, not achieving statistical significance (control: *r*=.20, *P*=.63; USN: *r*=.67, *P*=.10). Additionally, we examined whether patients with USN showed systematic differences in motion duration between left and right sides. Despite a mean difference of −80 ms, the median difference was effectively zero (0.8 [-204 to 63] ms), and a zero mean hypothesis could not be rejected (*P*=.58).

Usability

Table 5 shows the median ratings for all usability questions. Patients rated the game as comfortable (median 4) and intuitive (median 5), with high scores for clear instructions (median 5), enjoyable gameplay (median 5), and balanced challenges (median 4). Participants generally felt the game was engaging (median 4) and appropriately paced (median 4), with minimal reports of stress (median 1) or overwhelm (median 1).

Table . Overview of the usability study questions and answers.

Question	Median
Interacting with the elements (eg, paper, stamp) was comfortable.	4
I intuitively understood how to interact with the elements (paper, stamp).	5
The game instructions were clear and easy to understand.	5
The game maintained my attention from beginning to end.	4
I enjoyed playing the game.	5
The challenges in the game were appropriate and well-balanced.	4
I felt overwhelmed while playing the game.	1
I was motivated to continue playing.	4
The game had a good pace—neither too slow nor too fast.	4
I felt stressed by the game.	1

Discussion

Accuracy and Availability of Hand Tracking and Torso Rotation

The HoloLens standalone method clearly demonstrates the tracking loss issue described in the Introduction. The data from the ZED 2i, while achieving excellent availability, suffered from both higher systematic errors, likely due to coordinate system misalignment, and significant noise, resulting in poor overall accuracy. Our fusion approach combined advantages of both sources, achieving better tracking accuracy than the HoloLens 2 while maintaining near-complete availability.

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Torso angle tracking achieved high availability with no systematic bias, as evidenced by the small median signed angle error (0.26°). However, the median absolute angle error of 1.45° is relatively large compared to the clinical effects found during the search behavior phase, limiting the confidence in these results. This could possibly be improved in the future by ensuring better alignment between the external tracking system and the HoloLens 2 coordinate system.

Biased Search Behavior in Patients With USN

The analysis of the MGP during the search phase revealed, as expected, an ipsilesional shift in the patients with USN with respect to the table center. This was consistent with previously recorded behavior of patients with USN [43-45]. The shifted MGP also explains the prolonged time until papers on the contralesional side were found.

A significant feature of our method compared to traditional eye tracking during FVE is that it allows for free rotation of the head and torso. Analyzing the search behavior with this approach revealed that patients exhibited a bias of their head rotation toward the ipsilesional side, aligning with their gaze direction. Moreover, some patients rotated their trunks slightly toward the contralesional side, although this was not a behavior that achieved significance among the USN group. Nonetheless, this prompts further investigation into the observed behavior, as trunk orientation is known to define the reference frame for visual neglect. Hence, a rotation toward the contralesional side could have reduced the attentional bias to a certain degree in those patients, as reported by [19,20,46]. In general, these findings emphasize the importance of measuring torso rotation for a comprehensive assessment of USN symptoms.

The control group exhibited a slight leftward bias of their head rotation relative to the table, which can be explained by the intrinsic left-to-right scanning tendency, sometimes associated with reading direction, and right-hemispheric dominance for attention prevalent among healthy individuals [47,48].

Lateral Differences in Timing of Gaze Anchoring

The observed difference in gaze anchoring timing between the left and right sides encourages the hypothesis that neglect may impact eye–hand coordination in the USN group, though this remains a preliminary finding. In both groups, users generally initiated the motion from the ink pad to the paper "blindly," relying initially on the remembered position of the paper. However, in the USN group, the results indicate that gaze anchoring occurs earlier in the motion for targets on the left compared to the right.

Several factors may contribute to this asymmetry. First, the USN group might have put less trust in their memorized target positions on the left side, prompting them to fixate on those targets sooner. Supporting this theory, previous works have reported increased localization errors on the contralesional side [49]. According to [50], the visuospatial working memory was negatively affected after patients shifted their attention toward stimuli ipsilesional to the memorized location. In our experiment setup, such a stimulus was present, as the stamping task involved an attentional shift back to the centrally positioned ink pads, requiring patients to memorize a contralesional location. Additionally, reaching with the right hand toward a target on the left may also have induced an intermediate attentional shift toward the ipsilesional side, reinforcing this effect.

Second, differences in movement duration could partially account for the gaze anchoring asymmetry [42]. We observed a moderate correlation between lateral differences in gaze timing and movement in the USN group (r=.67, P=.10). However, the movement duration differences showed high variability and no consistent lateral pattern. This suggests that those differences cannot fully explain the gaze timing asymmetry. Given the small sample size, further investigation with a larger cohort is needed to clarify this potential contribution.

Usability

The positive feedback across several aspects of the framework and game suggests that it was accessible and motivating for users, supporting the feasibility of using it for more extensive clinical trials and during rehabilitation with patients with USN.

Limitations

First, the lack of a stroke-only control group (without USN) limits our ability to confidently attribute the observed effects specifically to USN. Additionally, substantial demographic disparities existed between groups, which are known to influence motor performance and limit the comparability of motor-related metrics between groups. Future studies should include a stroke control group without USN, matched on demographics, to better isolate USN-specific effects.

Second, both groups had relatively small sample sizes, with only seven patients in the USN group whose neglect severity varied from mild to moderate. This might have inflated the large effect size (Cohen d≈2.3) of the lateral difference in gaze-anchoring timing in the USN group. Replication with a larger cohort may be necessary to validate these findings.

Third, measurement precision of torso rotation was comparatively low and limits the confidence in the associated results. Fourth, to obtain the tracking accuracy results, the VICON data had to be spatially and temporally aligned to the HoloLens in postprocessing. Therefore, these results reflect tracking accuracy within the HoloLens' coordinate system rather than absolute world coordinates.

Despite these limitations, the results align with the hypothesized behavior of patients with USN, strengthening our confidence in the validity of the results.

Conclusions

In this work, we developed and validated a comprehensive behavioral tracking system for patients with stroke and USN that can capture eye, body, and hand movements during task execution in a mixed reality environment. By integrating a head-mounted AR display with an external body tracking system, we obtained naturalistic, multimodal interaction data in patients with stroke and USN. The system combines a game-like task with automated metric extraction and data visualization, offering a scalable tool for quantitative and qualitative behavioral assessment.

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Importantly, the system demonstrated a significant improvement in hand-tracking accuracy and availability over the standalone hand tracking of the HoloLens 2 or ZED 2i, with a fused hand-tracking error of 3.27 cm RMSE at 2.4% tracking loss.

In a proof-of-concept study with seven RBL patients with mild to moderate USN, the framework captured behavior consistent with known USN symptoms, such as ipsilesional gaze biases and delayed contralesional target detection.

The naturalistic task design combined with our system's multimodal data capture revealed new insights into USN visuomotor behavior. In particular, we discovered a pattern where patients directed their gaze toward movement targets earlier when those targets appeared on their contralesional side compared to their ipsilesional side.

This framework opens several promising research and clinical avenues. Larger patient cohorts and appropriate control groups could provide more robust quantitative insights into USN-related visuomotor deficits. Future investigations of nondominant hand use and bimanual coordination, and more extensive movement kinematic analysis, could reveal additional layers of motor-cognitive interaction in stroke recovery. Ultimately, this framework lays the groundwork for a truly comprehensive assessment of how USN manifests across the entire visuomotor cascade in a naturalistic setting.

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Data Availability

Public archiving of the data is not permitted under our ethics approval. In accordance with the Swiss Human Research Act, readers who wish to access the data and study materials should contact the corresponding author and complete a formal data-sharing agreement.

Authors' Contributions

JB and SK developed the app and implemented data processing. JB, DC, and QL conceived and designed the study. JB, DC, and TN recruited the patients and collected the data. JB, SK, DC, and QL analyzed and interpreted the data. JB, SK, DC, and QL drafted the report. All authors contributed to reviewing it; all authors read and approved the final manuscript.

Conflicts of Interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript.

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Abbreviations

AE: absolute error
AR: augmented reality
ATE: absolute trajectory error
FVE: free visual exploration
MGP: mean gaze position
Mocap: motion capture
RBL: right brain lesion
USN: unilateral spatial neglect
VR: virtual reality

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Assessing the Feasibility of Using Apple Vision Pro While Performing Medical Precision Tasks: Controlled User Study

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Abstract

Background: The emergence of next-generation video-see-through head-mounted displays, such as the Apple Vision Pro (AVP), has generated considerable interest in the medical field. While preliminary studies highlight AVP's potential, no controlled study has rigorously assessed its usability for precision-based medical tasks requiring fine motor control and real-world perception.

Objective: This study aims to evaluate the feasibility of using AVP while performing real-world medical precision tasks.

Methods: To assess AVP's feasibility, we conducted a controlled user study with 20 health care professionals, who performed 3 different suturing techniques across 3 intervention conditions. Participants completed the same tasks using AVP, the Microsoft HoloLens 2 (MHL2), and a baseline (without a head-mounted display). A within-subject design was used, ensuring that each participant experienced all intervention groups. We used a mixed methods research approach, incorporating both quantitative metrics, including task completion time, suturing performance, system usability score, cognitive load, virtual reality sickness, and presence score, as well as qualitative insights gathered through interviews.

Results: Participants took significantly longer to complete the entire task using AVP (570.0, SD 192.0 s) compared with MHL2 (456.0, SD 120.0 s; $P<.001$) and baseline (472.0, SD 143.0 s; $P<.001$). The analysis on participants' average suture performance revealed no significant differences across interventions ($P=.76$). The total raw NASA Task Load Index score among participants was significantly higher for AVP (43.9, SD 15.9) compared with MHL2 (21.5, SD 13.8; $P<.001$) and baseline (19.1, SD 15.1; $P<.001$). The analysis of the presence questionnaire demonstrated a significantly higher presence score for MHL2 (115.0, SD 11.4) compared with AVP (93.7, SD 12.7; $P<.001$). The overall virtual reality sickness questionnaire score was significantly higher for AVP (66.9, SD 19.8) compared with MHL2 (41.1, SD 9.32; $P<.001$). Moreover, the calculated system usability score for MHL2 (72.7, SD 8.54) was significantly higher compared with AVP (50.3, SD 14.4; $P<.001$).

Conclusions: In conclusion, AVP has potential for non–time-sensitive medical applications or those that emphasize digital elements over real-world interaction. Its current usability limitations, particularly increased cognitive load and prolonged task execution times, suggest that further optimizations are necessary before widespread clinical adoption is feasible.

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KEYWORDS

Apple Vision Pro; HoloLens; extended reality; precision task; head-mounted display

Introduction

Mixed reality (MR) has been a transformative technology for several years, revolutionizing various industries and applications. As part of the broader spectrum of immersive technologies [1], MR bridges augmented reality (AR), which overlays digital content onto the real world, and virtual reality (VR), which provides fully immersive digital environments. With recent advancements in wearable technology and head-mounted displays (HMDs), MR has expanded into a wide range of daily activities and professional domains [2]. A significant development in this field is the rise of extended reality (XR) devices, which integrate both AR and VR capabilities, enabling seamless transitions between immersive and real-world experiences. This new generation of devices, such as the Apple Vision Pro (AVP) [3], has sparked considerable interest and is believed to be the future of HMDs in the medical domain, offering users immersive XR experiences through video-see-through (VST) technology [4-12]. Although there are studies that have examined XR applications across

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various settings and domains, the choice of device and technology for specific task groups is often driven by the latest market trends rather than an informed assessment of their feasibility for the intended use case.

Egger et al [4,5] regarded AVP as a major step toward achieving the "ultimate display" for health care. They highlighted its potential to address challenges that previous MR devices, such as the Microsoft HoloLens (MHL) [13], encountered in terms of precision, reliability, usability, workflow integration, and user perception. Similarly, Masalkhi et al [6] postulated that Apple XR technology holds a wide range of possibilities in ophthalmology, including applications in surgical training, assistive devices, diagnosis, and education. Furthermore, Olexa et al [7] reported using AVP as a neurosurgical planning tool to visualize 3D models of patients. They noted that users found the 3D models to be highly realistic (Likert score of 4.5/5), the real-world view displayed through the headset to be natural (Likert score of 4.3/5), and experienced minimal eye strain or fatigue while using the device.

While these studies highlight the significant potential of AVP in the medical field and its ability to support the development of various beneficial applications, no controlled or experimental study has rigorously evaluated the usability of the device itself and its impact on user real-world performance and experience, independent of the application used. In particular, the suitability of AVP and its VST design remains unexplored in scenarios that involve wearing the headset while performing real-world, delicate tasks requiring fine motor control and precision, such as those encountered in surgical support and navigation systems. As immersive technologies continue to evolve, the extent to which the choice of device directly influences user performance remains unclear. Furthermore, while VST devices, such as AVP, are expected to enhance the accuracy and precision required for medical tasks by providing higher-quality visualization and more robust registration of digital objects, the usability of these technologies and the devices themselves for applications requiring real-world precision remains uncertain, as users rely on visual information through a video stream rather than direct visual perception. Consequently, the safety and feasibility of AVP in critical applications, such as in situ surgical navigational systems, need to be investigated. Additionally, its proclaimed superiority over existing HMDs in medical domains, which demand high levels of accuracy and dexterity, remains unproven. This gap presents an important opportunity for further research to substantiate the benefits and advantages of different XR approaches, including optical see-through (OST) and VST.

Many of the applications envisioned for AVP have already been achieved using MHL, an OST MR device series that has demonstrated a broad range of applications in medicine. These include patient data visualization [14], patient education [15], assistance and monitoring [16], preoperative diagnosis [17], anatomy learning [18,19], intervention training [20], image-guided interventions [21], in situ surgical navigation [22-26], and telemedicine [27]. Extensive use has demonstrated the effectiveness of MHL in these areas and provides a strong baseline for evaluating new XR devices, such as AVP, particularly for medical applications that rely on MR capabilities rather than pure VR and require visual perception of the real world.

This study addresses these gaps by evaluating the feasibility of AVP for performing medical precision tasks that require visual perception of the real world. The main goal of this study is to evaluate the feasibility of the devices and their underlying technology without any bias from specific applications. This work contributes to understanding the impact of device choice on user performance by examining both objective performance metrics and subjective measures of user experience. To achieve this, we designed a controlled user study involving 20 health care professionals, comparing AVP against a baseline (without an HMD) and an extensively used MR glass in the medical domain [14-22,24,25,28], MHL2, for performing 3 different suturing techniques. Our evaluation included both quantitative data, including the system usability score, task completion time (TCT), suturing performance, cognitive load, VR simulation sickness, and presence score, as well as qualitative data gathered through interviews.

Methods

Study Design and Protocol

This study adopts mixed methods research methodology, combining both quantitative and qualitative data collection approaches. Three interventions were designed, corresponding to the 3 conditions of the study: baseline (no HMD), MHL2, and AVP. The baseline (no HMD) condition was included to serve as a reference point for evaluating the effects of the other interventions. MHL2 was used due to its extensive prior use in the medical domain. A within-subject design was used, meaning that each participant participated in all studied interventions. The order of participation in each intervention was counterbalanced to mitigate potential order bias.

The study began with an introduction phase involving obtaining informed consent and an introduction to the study tasks from all participants. Following consent, the entire session was recorded using 2 cameras, one egocentric and one exocentric, with front-facing views. Later, participants were randomly assigned to 1 of 6 possible orders for performing the 3 interventions (baseline, MHL2, and AVP). Prior to task execution, participants completed 2 questionnaires on demographics and affinity for technology interaction [29].

Following completion of the preparation and order assignment, the experiment task began. During this stage, participants were asked to perform the same study task, which involved working with 3 different suture types, for each intervention. Prior to performing the study task with AVP and MHL2, calibration procedures were conducted. For MHL2, only eye calibration was performed. For AVP, both eye and hand calibration were performed to address any potential issues arising from lens misalignment or visual discrepancies.

After completing the task for each intervention, photographs of the participants' performance using the suturing kit were captured for subsequent evaluation. Additionally, web-based questionnaires were administered to evaluate key factors related to the user experience. Cognitive workload was assessed using

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NASA Task Load Index (NASA-TLX) [30], VR-induced sickness was measured with the virtual reality sickness questionnaire (VRSQ) [31], and the sense of presence in the digital environment was evaluated using the presence questionnaire (PQ) [32]. Furthermore, for a rapid and reliable assessment of new health care technologies [33], UMUX-Lite questionnaire was used. System usability score was then predicted using a regression equation based on the 2 UMUX-Lite items [34]. The order of questions was presented in a random order for each participant. After completing the task for the baseline condition (without an HMD), participants completed only the NASA-TLX [30]. Following the MHL2 and AVP interventions, participants filled out the NASA-TLX, VRSQ, PQ, and UMUX-Lite.

Finally, at the end of each session, a researcher conducted a short semistructured interview with the participants, asking them to reflect on their experience with each device. The interview questions encapsulated aspects including comfort, self-performance evaluation, pros and cons, and potential use cases.

After all data recording sessions were completed, the TCTs were extracted from the recorded videos. A researcher, who was blinded to the study's aims, measured the TCT for each suture performed by every participant. To ensure an objective evaluation of the time spent solely on suturing, TCT was defined as the duration from the moment the needle was grasped by the needle holder until the knot was cut with scissors. Additionally, 5 surgeons (7.2 [SD 1.7] years of surgical experience), who were also unaware of the study aims, evaluated suture performance based on anonymized photographs of performed sutures. All of the captured photographs of participants' performed sutures were presented in a random order to evaluator surgeons using a custom visualization tool. They rated the performance of each suture type separately on a scale of 0 to 100, considering factors such as the overall effectiveness of the suture, bite (length of the stitch across the wound), pitch (interval between stitches), and cosmetic appearance [35].

Study Task

To assess the feasibility of using AVP while performing precision-dependent medical applications and compare it with MHL2 and baseline (no HMD), we designed a controlled user study task that incorporates performing different suture techniques. Since the main goal of this study was to evaluate the usability of the device and its underlying technology without any bias from specific applications, no digital information was displayed in the HMDs used in this study (AVP and MHL2). The participants were instructed to perform the suturing task either using one of the HMDs or without any HMD in the baseline condition. This approach is particularly important for delicate tasks requiring fine motor control and precision in real-world applications such as surgery, where the device itself may affect task performance regardless of the usability of the XR application used. By isolating the device from application-related factors, this ensured an unbiased assessment of its usability, preventing findings from being influenced by app design or content. The study included 3 types of sutures, each requiring progressively more complex techniques, ranging from basic to advanced. The simple interrupted suture (SIS, Figure 1A) was selected as the simplest task, while the vertical mattress suture (VMS, Figure 1B) and continuous subcuticular suture (CSS, Figure 1C) were chosen for their complexity. These techniques rely on correct depth perception, as they involve inserting a suturing needle into a specific layer of the skin [35], making them ideal for evaluating users' ability to perceive depth in a simulated environment.

A suture training kit [36] was used as the base for performing the sutures. All participants were asked to complete 3 SIS, 3 VMS, and close a 5 cm long wound on the suturing kit using a CSS for each intervention. All sutures were performed using 3‑0 polypropylene [37] and the same clinical surgical instruments, including needle holder, tweezers, and scissors (Figure 2). To minimize potential bias in TCTs due to the length of the suture material, each suture type was performed with a new suture material.

Figure 1. The illustration of 3 suture types included in the study task: (A) simple interrupted suture, (B) vertical mattress suture, and (C) continuous subcuticular suture.

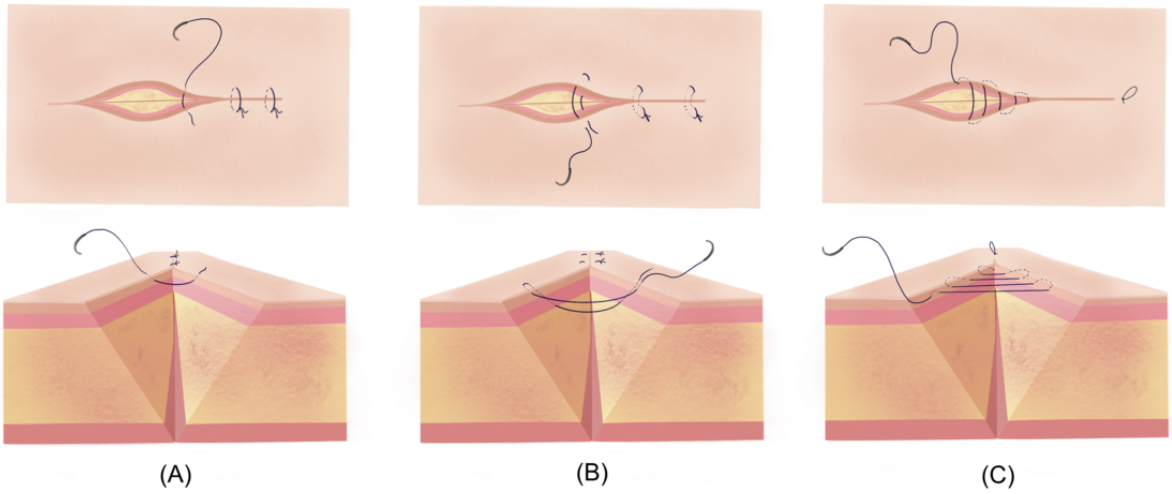

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Figure 2. The suture training kit used during study tasks containing a silicone suture pad and instruments.

Participant Recruitment

Recruitment was conducted through word-of-mouth and advertisements via mail. The experiment took place at Klinikum Saarbrücken, Germany. Participation was entirely voluntary, and no compensation was provided.

The inclusion criteria for participants required that they be health care professionals with prior experience in performing wound suturing on patients. Additionally, the study limited participation to individuals without vision disorders or those with minor refractive errors, who could complete the study tasks without eyeglasses. To minimize bias, participants with minor refractive errors who typically used eyeglasses were instructed to perform all tasks without glasses across all interventions.

Statistical Analysis

Sample size calculation was performed using the power analysis tool G*Power [38]. Since there is no previous work comparing participants' performance using the AVP against MHL2 and baseline, we hypothesized a large between-group effect size (Cohen *f*) of 0.40 based on personal experience. This assumption was used to calculate the required sample size. With a power of $1-\beta=.95$ and $\alpha=.05$, the required sample size was calculated to be 18 participants. To account for 10% potential dropouts, we included a total of 20 participants in the study.

Statistical analysis was conducted using the R project for statistical computing [39]. Continuous data were expressed as means (SD), while categorical data were reported as frequencies and proportions. The effects of the interventions (baseline, MHL2, and AVP) were analyzed within-subject using repeated-measures ANOVA. When the assumption of sphericity was violated, the Greenhouse-Geisser ($\varepsilon<.75$) correction was applied. For the repeated measures ANOVA, we reported the F-statistic, degrees of freedom, *P* value, and generalized eta squared ($\eta G2$) as a measure of effect size. For post hoc pairwise comparisons, we conducted paired-samples *t* tests with Bonferroni correction for multiple within-group comparisons and reported the adjusted *P* values along with Cohen *d* to indicate effect size. A 2-sided *P* value of <.05 was considered statistically significant for all analyses. Furthermore, the inter-rater agreement of the performance scores by 5 evaluator surgeons was confirmed using the rwG(J) agreement index [40].

Qualitative Analysis

All interviews conducted in this project were transcribed verbatim. We adopted a pragmatic approach to qualitative analysis, as recommended by Blandford et al [41]. Initially, 2 researchers independently analyzed the same 25% of the data. Based on iterative discussions, a preliminary coding framework was developed. The remaining 75% of the interview data were then evenly distributed between the 2 researchers for coding using the established coding framework. To further ensure the consistency between final codings in case of new code emergence or coding disagreements, in a final discussion, the coding framework was further refined, leading to the development of the main themes.

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Ethical Considerations

Before conducting the study, ethics approval was obtained from the institutional ethical review board of the German Research Center for Artificial Intelligence (DFKI, IRB approval number: VST – 48/25). All participants received comprehensive information about the objectives and data handling involved in this study. Data collection only proceeded after obtaining their voluntary informed consent. All participants were assured that their contributions would remain anonymous and were offered the opportunity to withdraw from the study at any stage prior to publication. All data were stored securely at the DFKI local server. Each participant signed a written consent form. No financial compensation was offered or provided.

Results

Study Population and Demographics

In total, 20 health care professionals participated in this study. The demographic characteristics of the participants are detailed in Table 1.

Table . Demographics of study participants.

Characteristics	Value
Gender, n (%)	
Man	14 (70)
Woman	6 (30)
Age (years), mean (SD)	33.65 (7.60)
Occupation, n (%)	
Surgeon	15 (75)
Physician assistant	1 (5)
Medical intern	4 (20)
Participants with minor refractive errors, n (%)	6 (30)
Clinical experience (years), mean (SD)	7.8 (6.45)
Prior use of OST[a] HMDs[b] (1 - 5 Likert scale), mean (SD)	1.8 (0.93)
Prior use of VST[c] HMDs (1 - 5 Likert scale), mean (SD)	1.35 (0.63)
Affinity for technology interaction (1 - 6 Likert scale), mean (SD)	3.83 (0.79)

[a]OST: optical see-through.

[b]HMD: head-mounted display.

[c]VST: video-see-through.

User Performance

Suturing Performance

The 5 surgeons' evaluation scores of participants' suture performances showed high agreement, with an rwG(J) value greater than 0.99 across the suture types. The analysis on participants' average suture performance revealed no significant differences across interventions (baseline=73.8 [SD 13.5], AVP=74.5 [SD 10.0], MHL2=75.3 [SD 9.7], $F_{2,38}$=0.28, P=.76, ηG2=0.003). Despite the worsened performance with AVP for all suture types, no significant differences were observed between interventions for any suture type (Figure 3).

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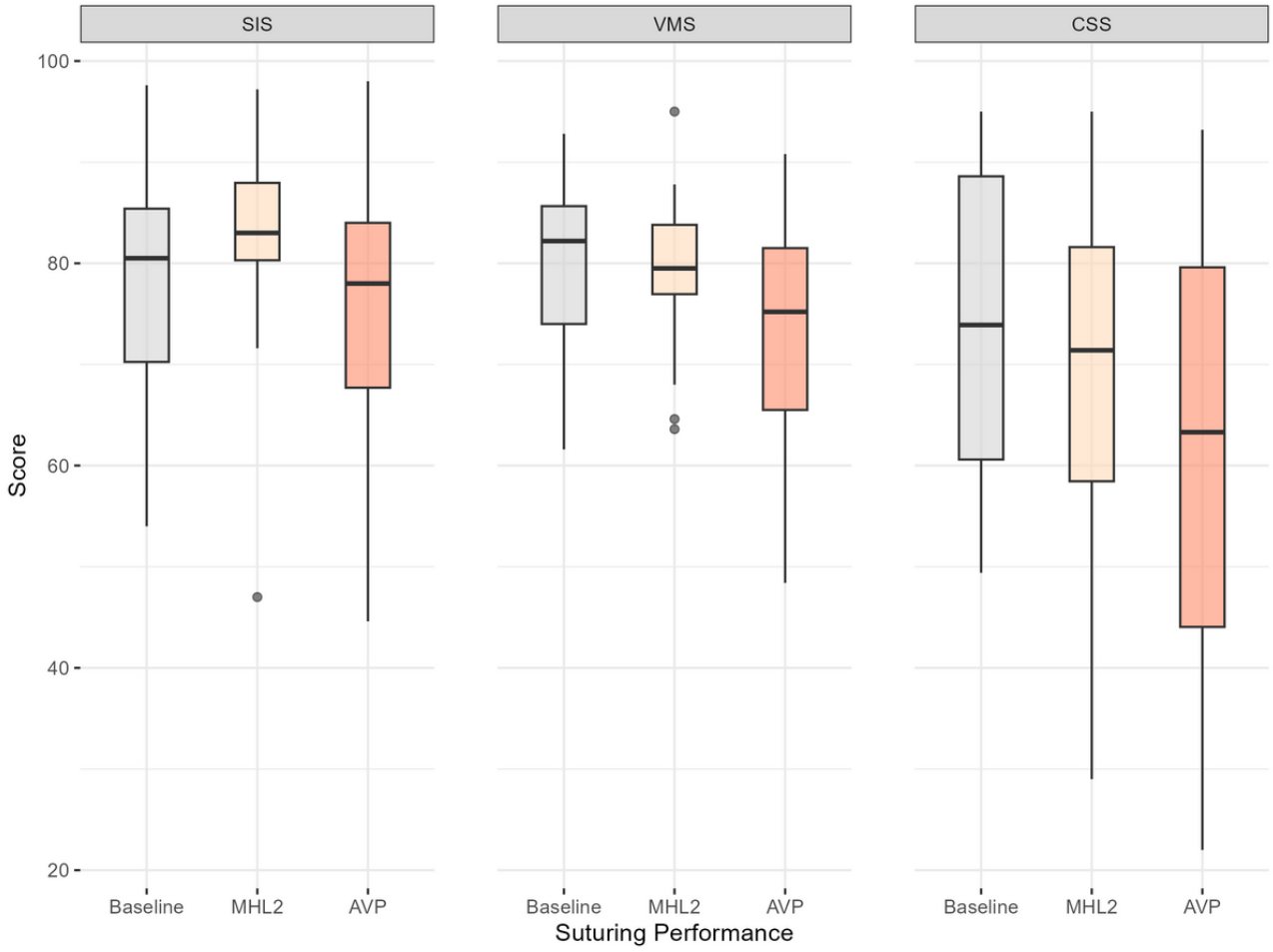
Figure 3. The participants' suturing performance rated by surgeons across different suture types. AVP: Apple Vision Pro; CSS: continuous subcuticular suture; MHL: Microsoft HoloLens; SIS: simple interrupted suture; VMS: vertical mattress suture.



Task Completion Time

The analysis revealed a significant difference in the TCT required to complete all tasks across the interventions (baseline=472.0 [SD 143.0] s, AVP=570.0 [SD 192.0] s, MHL2=456.0 [SD 120.0] s; $F_{2, 38}$=17.6, P<.001, ηG2=0.101). Pairwise test results showed participants took significantly longer to complete the entire task using AVP to MHL2 (P<.001, Cohen d=1.02, large effect) and baseline (P<.001, Cohen d=1.03, large effect). The comparison between baseline and MHL2 showed a small effect size (P=.30, Cohen d=0.2, small effect), suggesting minimal difference.

Analysis performed on TCT for each individual suture type (Figure 4) revealed that there were no significant differences in the time required to perform SIS across the interventions (baseline=122.2 [SD 48.9] s, AVP=139.8 [SD 76] s, MHL2=117.5 [SD 37.5] s; $F_{1.4, 27.0}$=3.67, P=.05, ηG2=0.03). However, a significant difference was observed for more complex tasks, VMS (baseline=166.8 [SD 64.2] s, AVP =195.9 [SD 79.6] s, MHL2=161.2 [SD 63.4] s; $F_{1.5, 28.8}$=9.66, P=.001, ηG2=0.048) and CSS (baseline=182.9 [SD 59.1] s, AVP =234.7 [SD 83.6] s, MHL2=177.0 [SD 52.8] s; $F_{1.4, 27.3}$=11.7, P<.001, ηG2=0.138).

Pairwise test results showed participants required significantly more time to complete VMS using AVP compared with MHL2 (P<.001, Cohen d=1.0, large effect) and baseline (P=.04, Cohen d=0.6, moderate effect). The comparison between baseline and MHL2 showed no significant difference (P=.99, Cohen d=0.2, negligible effect).

Similarly, for CSS, a significantly longer time was needed when using AVP compared with MHL2 (P=.007, Cohen d=0.8, moderate effect) and baseline (P=.002, Cohen d=0.9, large effect). No significant difference was observed between baseline and MHL2 (P=.99, Cohen d=0.1, negligible effect).

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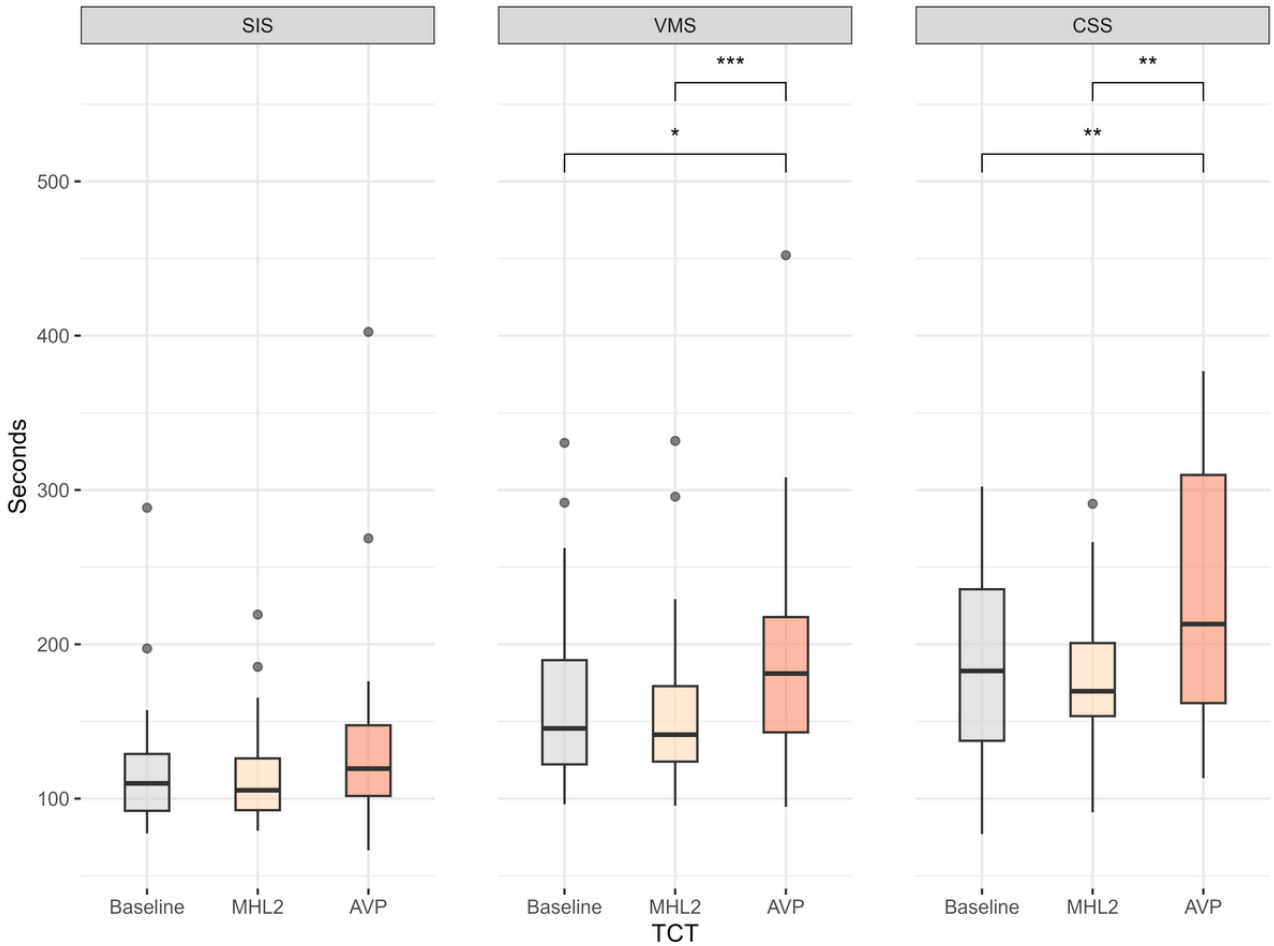
Figure 4. Participants' TCTs across different suture types. Statistically significant differences are denoted as follows: **P*<.05, ***P*<.01, and ****P*<.001. AVP: Apple Vision Pro; CSS: continuous subcuticular suture; MHL: Microsoft HoloLens; SIS: simple interrupted suture; TCT: task completion time; VMS: vertical mattress suture.



User Experience

Cognitive Workload

The analysis revealed a significant difference in the total raw NASA-TLX score across the interventions (baseline=19.1 [SD 15.1], AVP=43.9 [SD 15.9], MHL2=21.5 [SD 13.8]; $F_{1.2, 21.9}$=28.6 *P*<.001, ηG2=0.37). The pairwise test results showed the total raw NASA-TLX score among participants was significantly higher for AVP compared with MHL2 (*P*<.001, Cohen *d*=1.2, large effect) and baseline (*P*<.001, Cohen *d*=1.3, large effect). No significant difference was observed between baseline and MHL2 (*P*=.30, Cohen *d*=−0.401, negligible effect).

Analysis on each scale of NASA-TLX showed significant differences on mental demand (baseline=20.2 [SD 18.0], AVP=46.0 [SD 22.9], MHL2=23.75 [SD 18.6]; $F_{1.2, 22.8}$=21.1, *P*<.001, ηG2=0.256), physical demand (baseline=17.2 [SD 17.3], AVP =46.0 [SD 25.0], MHL2=19.2 [SD 14.3]; $F_{1.1, 21.3}$=22.4, *P*<.001, ηG2=0.324), performance (baseline =18.2 [SD 16.5], AVP =45.5 [SD 21.2], MHL2=20.7 [SD 16.6]; $F_{1.2, 22}$=3.6, *P*<.001, ηG2=0.3), effort (baseline=24.5 [SD 23.4], AVP =56.0 [SD 20.0], MHL2=28.0 [SD 18.0]; $F_{1.3, 24.5}$=23.4, *P*<.001, ηG2 =0.3), and frustration (baseline=12.25 [SD 11.7], AVP=43.5 [SD 23.4], MHL2=15 [SD 12.1]; $F_{1.1, 21}$=26.1, *P*<.001, ηG2=0.4) factors. Pairwise analysis showed significantly higher scores for AVP compared with MHL2 for mental demand (*P*<.01, Cohen *d*=1.0, large effect), physical demand (*P*<.001, Cohen *d*=1.2, large effect), performance (*P*<.001, Cohen *d*=1.0, large effect), effort (*P*<.001, Cohen *d*=1.1, large effect), and frustration (*P*<.001, Cohen *d*=1.1, large effect). Similarly, significant differences were observed for AVP compared with baseline on mental demand (*P*<.001, Cohen *d*=1.1, large effect), physical demand (*P*<.001, Cohen *d*=1.0, large effect), performance (*P*<.001, Cohen *d*=1.1, large effect), effort (*P*<.001, Cohen *d*=1.1, large effect), and frustration (*P*<.001, Cohen *d*=1.2, large effect). No significant difference was observed between MHL2 and baseline on any of the NASA-TLX factors (Figure 5).

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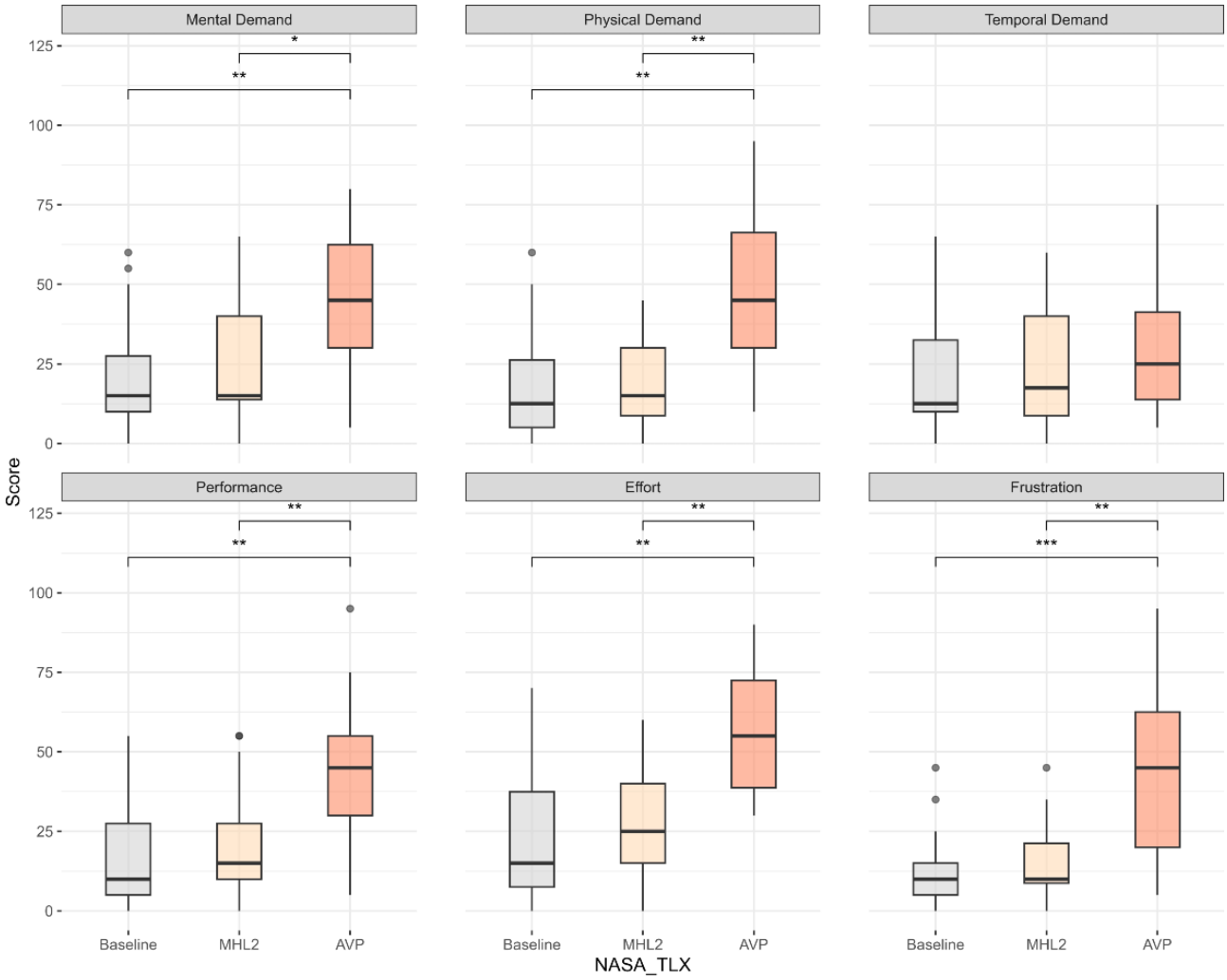
Figure 5. NASA-TLX results for each factor (mental demand, physical demand, temporal demand, performance, effort, and frustration) across the 3 interventions. Statistically significant differences are denoted as follows: *P<.01, **P<.001, and ***P<.0001. AVP: Apple Vision Pro; MHL: Microsoft HoloLens; NASA-TLX: NASA Task Load Index.



Presence

The analysis of PQ demonstrated a significantly higher presence score (AVP=93.7 [SD 12.7], MHL2=115.0 [SD 11.4]; $F_{1, 19}$=27.9, P<.001, ηG2=0.4) for MHL2 compared with AVP. This significant difference was observed in all factors of presence including the realism (AVP=34.2 [SD 4.9], MHL2=41.0 [SD 5.3]; $F_{1, 19}$=17.2, P<.001, ηG2=0.3), possibility to act (AVP=20.6 [SD 3.5], MHL2=25.5 [SD 2.8]; $F_{1, 19}$=19.8, P<.001, ηG2=0.4), quality of interface (AVP=14.8 [SD 3.5], MHL2=18 [SD 3.0]; $F_{1, 19}$=19.7, P<.001, ηG2=0.2), possibility to examine (AVP=13.9 [SD 3.6], MHL2=18.3 [SD 2.3]; $F_{1, 19}$=20.1, P<.001, ηG2=0.4), and self-evaluation of performance (AVP=10.2 [SD 2.8], MHL2=12.2 [SD 2.0]; $F_{1, 19}$=5.5, P=.03, ηG2=0.1).

VR Sickness

The overall VRSQ score (AVP=66.9 [SD 19.8], MHL2=41.1 [SD 9.32]; $F_{1, 19}$=46.7, P<.001, ηG2=0.4) was also significantly higher for AVP compared with MHL2. The participants rated significantly higher scores on both oculomotor (AVP=75.8 [SD 22.9], MHL2=42.9 [SD 12.8]; $F_{1, 19}$=69.8 P<.001, ηG2=0.4) and disorientation (AVP=58 [SD 19.0], MHL2=39.3 [SD 9.15]; $F_{1, 19}$=18.9, P<.001, ηG20.3) factors for AVP compared with MHL2.

System Usability

System usability score for MHL2 was significantly higher compared with AVP (AVP=50.3 [SD 14.4], MHL2=72.7 [SD 8.54]; $F_{1, 19}$=34.4, P<.001, ηG2=0.5).

Interviews

Overview

After thematic analysis of the interviews, we developed 5 main themes: comfort and physical strain, visual challenges and depth perception, self-evaluation of performance, user confidence and preference, and application domain.

Comfort and Physical Strain

Thematic analysis of observations made during the study revealed several comfort-related issues associated with AVP. Participants reported discomfort due to the unbalanced weight distribution, with the majority of the weight concentrated on the nasal and maxillary area, leading to strain in the back neck

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muscles and headaches. Two participants commented on this with the following statements:

> *When you look straight it is more convenient but when you bend your head to look at the stitch pad which I think would be the normal case when you operate around the table, then it is too uncomfortable, because the whole weight is in front and there is a constant contraction on your neck.* [P9, surgeon]

> *I usually get VR sickness whenever I use VR headsets. I tested AVP before and previously didn't have any issues when watching videos and so on, but here I got a very bad headache because I think I tried too much to focus and finish my task.* [P1, surgeon]

Additionally, they described a sensation of instability when focusing on a task for an extended period, expressing that it felt as though their head might fall forward.

> *It [AVP] is very heavy and after a while you feel like your head would fall down if you don't consistently fight it. And I can assure you it was a relief to take it out.* [P13, surgeon]

In contrast, no incidents of discomfort were observed with MHL2 for the period the participants used MHL2 for the experiment. One of the participants also indicated that the design of MHL2 is more comfortable and suited for use in the operating room compared with AVP.

> *We didn't use it here, but I guess with HoloLens you have also this option where you could push the visor up or down based on what you want to see but with AVP you don't even have that option. You just have to take it off completely. And it is just not practical to use it during operation if you have to take it off every time.* [P1, surgeon]

Visual Challenges and Depth Perception

Participants also experienced visual challenges with AVP, including blurred vision and difficulties with depth perception. The struggle with depth perception further impacted their ability to accurately judge distances, which is critical for suturing.

> *My vision felt a bit blurry; I could not see the details I had difficulties to see the needle and also to do the knots.* [P12, surgeon]

> *For the first two sutures AVP was also ok but for the last suture type you have to really see where you put your needle in and that was simply impossible to make sure you are in the correct layer.* [P11, physician assistant]

> *I don't think that my hand and eye coordination was disturbed, but it was very difficult to estimate the depth, there was like less contrast compared to reality.* [P4, surgeon]

Participants also reported that the sharpness of the view varied depending on the distance of the objects from them. Some noted that maintaining a greater distance provided a sharper view; however, this was not ideal for delicate tasks, as they naturally tended to lean in for a closer observation and better precision.

> *I could see things clearly farther than one meter to me. I could even read small letters, but when I looked at the stitching pad which was closer to me then it became blurry. And got even blurrier when I was leaning closer to it to do the stitches. Which usually you should see better when you get closer, but it just made it worse.* [P13, surgeon]

Self-Evaluation of Performance

Some participants believed that AVP negatively impacted their performance compared with MHL2 and baseline.

> *I used AVP before, but I only used it to watch videos, and initially I thought AVP would be better compared to HoloLens, but it was a complete catastrophe. I almost saw nothing. Yes, I did sutures from experience, but it was a complete guess work especially for the last suture type.* [P1, surgeon]

> *Naturally you realize a difference between no glass and having glass for both devices. But the difference was simply too much for AVP that I think it really impacted my performance.* [P11, physician assistant]

> *The HoloLens was not a big influence in my performance compared to performing without one it felt like having a light shaded sunglass on. If you look through the screen the vision is a bit darker but doesn't make your performance worse. AVP is very immersive but for precise work like stitches it's not fast enough and the resolution is not optimal.* [P4, surgeon]

User Confidence and Preference

Participants expressed a preference for OST over VST. They reported that VST created a sense of disconnection from the real world, which was also evident in the lower presence score compared with OST. They reported that in real-life scenarios involving patients, it would impact their confidence. In contrast, OST allowed them to maintain situational awareness and benefit from a wider peripheral vision, enhancing their overall experience and performance. Participants reflected on this, saying:

> *With HoloLens I felt more secure, because I think my peripheral vision was not affected that much but in AVP even though you still see but you have more restricted peripherals.* [P2, surgeon]

> *I think optimally the best is no glass but if I should choose, I think when you talk to a patient or your colleagues around the surgery table it feels just more natural to have eye contact even if it is through a glass like this [showing MHL2]. It is better than having a big headset on your face where no one can see your eyes in there. It is just more assuring with a see-through glass than a completely closed one [AVP].* [P18, surgeon]

Application Domain

The participants regarded MHL2 as a usable device for various medical applications, including applications for intraoperative use. However, they believed that AVP would be more suitable

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for domains such as training or surgical planning, where the device would not be used during actual patient operations.

> *I think both devices could be used for medical domain, but I won't feel comfortable operating with the first one [AVP]. I think it is risky if you operate on veins or arteries. I don't want to take any risk when operating on a patient.* [P2, surgeon]

> *I see HoloLens as a usable device during operation, it won't stress you, but AVP would be a better fit for training or teaching or perhaps surgery planning.* [P8, surgeon]

A participant also suggested that AVP could be used for surgical applications, such as laparoscopic surgery, where the surgical field is already viewed through high-resolution video.

> *I think AVP would be useful for laparoscopic surgery where your view to the operation scene is already through a video and with AVP you can have this high-quality video stream.* [P1, surgeon]

Discussion

Overview

With advancements in computational power, camera technology, and display systems, a noticeable trend is emerging in commercially produced HMDs. Manufacturers are increasingly shifting from dedicated AR and VR HMDs toward XR HMDs capable of supporting both functionalities. This transition is also evident in the evolution of recent HMDs developed by well-known brands, such as Apple [3] and Meta [42], which use VST displays, in contrast to earlier designs like Microsoft's HoloLens [13], which relied on OST technology. Although this transition is expected to bring advantages beyond simply combining AR and VR, such as a wider field of view, higher camera quality, brightness control, and ultimately more precise spatial registration of digital objects, its feasibility in domains requiring high precision, such as intraoperative use, remains untested. Despite the foreseen potential benefits that recent XR glasses could bring to the medical domain [4,5,12], their feasibility in high-precision medical applications remained an open question. While most related studies focus on evaluating specific immersive applications within this domain [7,28,43], the choice of used devices is often driven by market trends rather than a critical assessment of their suitability for the intended use. Although some studies have compared the technical capabilities of different HMDs, including VST and OST design [44-46], they often overlook user experience and performance outcomes.

The findings of this study underscore the importance of device selection, particularly in time-sensitive and precision-dependent medical contexts. As progressively more immersive HMDs are being produced, our results demonstrate that the appropriateness of the chosen device itself plays a pivotal role in the user's real-world performance—even before any application is introduced. Neglecting to assess the suitability of the device as an initial step may contribute to the negative user experience and delayed integration of immersive technologies in clinical settings, as the hardware itself may be ill-suited for the domain—even when the application might offer substantial potential benefits.

Principal Results

In this study, we evaluated the feasibility of AVP (the most recent and promising XR HMD for the medical domain [10,12]) with MHL2, the commonly used MR HMD in the medical domain for precision tasks [14-22,24,25,28]. Twenty health care professionals participated in the study, performing suture tasks under 3 conditions: AVP, MHL2, and a baseline condition without an HMD. We evaluated user performance and experience across these conditions. Post hoc analysis of the primary outcome measures revealed a large observed effect size between AVP, MHL2, and the baseline, suggesting that the sample size (n=20) was adequate and confirming the validity of our initial power analysis. Our findings highlight the distinct strengths of each HMD, suggesting their suitability for different medical use cases.

A key observation from our study was the significant increase in cognitive load when using AVP compared with MHL2 and the baseline condition. This higher cognitive burden was accompanied by increased TCTs, indicating that AVP demands a greater cognitive workload from users. Interestingly, despite these challenges, objective performance evaluations did not show significant differences across the interventions. However, participants' self-reported performance, as captured in the PQ, indicated a significant decline compared with MHL2. This divergence between expert-assessed performance scores and self-evaluations may reflect a reduction in participants' confidence in their task performance, a sentiment that was also echoed in the interview responses.

These findings suggest that AVP remains a feasible option for non-time-sensitive medical domains where cognitive workload and TCT are not critical factors, such as a surgical planning tool demonstrated by Olexa et al [7], where there is no trade-off between the benefits of the used application and the need for real-world precision and speed.

Moreover, AVP potentially stands as a feasible device for medical education and training, incorporating virtual reality simulations where interaction with digital elements is prioritized over real-world precision. However, the usability of AVP while training precision tasks in the real world might be limited. A participant's sentiment on performing sutures from experience instead of relying on their visual perceptions indicates that training real-world precision tasks with AVP could potentially cause negative impacts on the learning process. A device that inadvertently increases cognitive demand or induces disorientation, as observed with AVP (Figure 5), might lead to suboptimal skill acquisition, potentially compromising the training outcomes. In educational contexts, the choice of XR technology can significantly influence learning behavior. Although positive outcomes have been demonstrated in nonmedical areas such as design education [47] over nonimmersive devices, the choice of immersive devices should still be carefully considered in educational settings, particularly those that emphasize psychomotor skills. An educational XR system that imposes excessive cognitive workload or fails to foster a strong sense of presence may lead to the development

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of maladaptive motor patterns or “incorrect” muscle memory, ultimately impacting long-term real-world performance.

Furthermore, AVP could serve as a practical solution for applications where direct real-world perception is either not required or is transmitted to the device instead of being captured by it, such as in telemedicine. Similarly, in fields where user presence is essential but critical information is traditionally delivered through digital interfaces, like laparoscopic surgery, where surgeons view the operative field on a 2D monitor, the potential of AVP could be further explored and leveraged. However, for use cases that involve fine motor tasks, such as those suggested by previous works including medical training scenarios [10,48] or in more critical applications such as intraoperative support tools [48], the increased workload and disorientation associated with AVP might hinder user real-world performance. Conversely, MHL2 demonstrated its suitability for applications requiring high precision and time efficiency. Its OST design allowed for a lower cognitive load and better user experience during the suturing task, with no significant differences when compared with the baseline. This underscores its potential for intraoperative use cases, such as surgical navigation and other real-time assistance tools, where maintaining a strong connection to the real world is critical.

Unlike the findings of the study by Olexa et al [7], where participants reported minimal eye strain or fatigue, our questionnaire responses on VR sickness indicated heightened oculomotor strain and disorientation with AVP. This discrepancy could be attributed to differences in user attention directed toward digital versus real-world objects. In the study by Olexa et al [7], users primarily focused on digital objects, whereas in our study, the main focus was on real-world perception. This phenomenon was also corroborated by one of our participants, who had prior experience using AVP. In our study, participants frequently reported that AVP caused physical discomfort—including eye strain, headaches, and neck fatigue—as well as visual challenges such as blurriness, difficulty focusing, and disorientation during head movement. These sensory and ergonomic limitations often led to reduced task confidence and greater reliance on prior experience or instinct rather than real-time visual feedback. In contrast, MHL2 was consistently described as lightweight, comfortable, and minimally intrusive, with clearer visual output and fewer disruptions to the user’s natural workflow. Such qualitative insights underscore the critical role of comfort and visual clarity in sustaining task engagement and motor coordination over time. These human-centered considerations are especially relevant in domains where extended use or precision is essential. AVP, in its current form with display quality and ergonomic constraints, may be more suitable for fully immersive VR applications rather than AR/MR-integrated medical use, particularly for shorter durations. In contrast, MHL2 demonstrated lower VR sickness scores, attributed to its OST design, along with a more balanced weight distribution and higher presence scores. These features position MHL2 as better optimized for applications requiring extended use periods and seamless real-world connectivity.

The findings of this study highlight several factors that could inform the future design of XR and MR devices for the medical domain. While generalizability remains a goal for widespread adoption across diverse medical applications, custom designs may be more appropriate for time-critical use cases, such as surgical navigation systems. The optimal approach may vary depending on the method used to visualize the surgical scene, whether open surgery, laparoscopic, or robotic-assisted procedures. For open surgery, OST displays could provide distinct advantages by preserving a clear view of the real world and facilitating seamless communication with the surgical team. Conversely, in scenarios involving indirect surgical views, such as laparoscopic procedures, VST HMDs might offer greater benefits. Furthermore, the future integration of VST HMDs in precision-demanding applications requires high-quality camera feed from a real-world environment; challenges such as camera focus issues, which result in blurring of the real-world video stream, can significantly hinder the usability of these devices in tasks requiring precision. Finally, ensuring comfort during extended use is critical for intraoperative tools. Features such as balanced weight distribution, antimicrobial coatings, and easy-to-clean surfaces would further facilitate smoother integration into clinical workflows.

Limitations

While this study provides valuable insights, it also has several limitations. First, we focused solely on evaluating the feasibility of AVP for medical precision tasks and compared the outcomes with MHL2 as a representative example of existing MR devices, given its extensive prior use in the medical domain. To further validate the generalizability of our findings regarding comparisons between various VST and OST displays, additional research involving other available HMDs is necessary. Second, our study included only participants with no or minor refractive errors who were able to complete the tasks without eyeglasses. To minimize bias, the 6 participants with minor refractive errors were asked to perform all tasks across all interventions without wearing eyeglasses. Although it is possible to wear eyeglasses with MHL2, this approach was not feasible for AVP due to its design. While there is an option to integrate correction lenses into AVP, customizing lenses for each participant was impractical and not feasible. Finally, while AVP is expected to enhance the display of digital objects, no digital elements were incorporated into the study tasks, as this was beyond the scope of our research. Our primary objective was to assess the safety and feasibility of AVP as a VST-HMD for performing medical precision tasks.

Conclusions

In conclusion, while AVP shows promise for non-time-sensitive applications that do not have an emphasis on real-world perception, MHL2 remains the preferred choice for time-critical and precision-demanding tasks. Further research and device refinements will be necessary to fully integrate XR HMDs into diverse medical applications, ensuring both user comfort and operational efficiency.

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Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

All authors have made substantial contributions to the article to meet the criteria for authorship. HJ and OG were responsible for the conceptualization of the study. The methodology was developed by HJ, PL, GAS, JK, and OG. Data recording and curation were conducted by HJ, VFR, and OG. Formal analysis was carried out by HJ, VFR, JK, and OG. PL and JK were responsible for funding acquisition. Supervision was provided by PL, GAS, JK, and OG. The original draft of the manuscript was written by HJ, VFR, and OG. All authors—HJ, VFR, PL, GAS, JK, and OG—contributed to the review and editing of the manuscript.

Conflicts of Interest

None declared.

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Abbreviations

AR: augmented reality
AVP: Apple Vision Pro
CSS: continuous subcuticular suture
HMD: head-mounted display
MHL: Microsoft HoloLens
MR: mixed reality
NASA-TLX: NASA Task Load Index
OST: optical see-through
PQ: presence questionnaire
SIS: simple interrupted suture
TCT: task completion time
VMS: vertical mattress suture
VR: virtual reality
VRSQ: virtual reality sickness questionnaire
VST: video-see-through
XR: extended reality

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