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Viewpoint

What is Diminished Virtuality? A Directional and Layer-Based Taxonomy for the Reality-Virtuality Continuum

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Abstract

The concept of reality-virtuality (RV) continuum was introduced by Paul Milgram and Fumio Kishino in 1994. It describes a spectrum that ranges from a purely physical reality (the real world) to a purely virtual reality (a completely computer-generated environment), with various degrees of mixed reality in between. This continuum is “realized” by different types of displays to encompass different levels of immersion and interaction, allowing for the classification of different types of environments and experiences. What is often overlooked in this concept is the act of diminishing real objects (or persons, animals, etc) from the reality, that is, a diminution, rather than augmenting it, that is, an augmentation. Hence, we want to propose in this contribution an update or modification of the RV continuum where the diminished reality aspect is more prominent. We hope this will help users, especially those who are new to the field, to get a better understanding of the entire extended reality (XR) topic, as well as assist in the decision-making for hardware (devices) and software or algorithms that are needed for new diminished reality applications. However, we also propose another, more sophisticated directional and layer-based taxonomy for the RV continuum that we believe goes beyond the mediated and multimeditated realities. Furthermore, we initiate the question of whether the RV continuum truly ends on one side with physical reality.

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KEYWORDS

reality-virtuality continuum; diminished virtuality; Apple Vision Pro; VR; virtual reality; reality-virtuality; mixed reality; augmented reality; XR; extended reality; taxonomy; classification; classifications; concept; concepts; conceptual

Introduction

The reality-virtuality (RV) continuum is a concept introduced by Paul Milgram and Fumio Kishino [1] in 1994. It describes a spectrum that ranges from a purely physical reality (the real world) to a purely virtual reality (VR; a completely computer-generated environment), with various degrees of mixed reality (MR) in between. This continuum is “realized” by different types of displays [2] to encompass different levels

of immersion and interaction, allowing for the classification of different types of environments and experiences. The RV continuum helps us understand the varying levels of immersion and interactivity that technology can provide. As technology advances, the boundaries between these immersion levels can become more fluid, and new hybrid experiences can emerge. The continuum is particularly relevant in fields such as VR, augmented reality (AR), and MR, where researchers and developers aim to create more compelling and natural

experiences that bridge the gap between the physical and virtual worlds. We used ChatGPT (OpenAI) [3] to gauge the current state of the RV continuum. According to ChatGPT, the continuum is often divided into several main categories (note,

we adapted the ChatGPT results and enhanced it with concrete examples, where necessary; [Textbox 1](#) [4]). The original ChatGPT transcript is shown in [Multimedia Appendix 1](#) [3].

Textbox 1. Main categories of the reality-virtuality continuum, modified from ChatGPT.

ChatGPT prompt:

- What is the reality-virtuality continuum?

Main categories (modified ChatGPT output):

- Physical reality (real environment): This is the state of the unmediated physical world, where all sensory perceptions are naturally experienced without any technological augmentation.
- Augmented reality (AR): In this category, virtual elements are overlaid onto the real world. AR enhances the user's perception of the physical world by adding computer-generated visual, auditory, or haptic information. Examples include smartphone apps that display digital information on top of real-world views, such as Pokémon GO [5].
- Mixed reality (MR): MR environments combine virtual and physical elements in a way that allows them to interact in real time. Users can manipulate both virtual and real objects, and the distinction between the 2 can be blurred. Microsoft's HoloLens is an example of an MR device that enables users to interact with holographic objects in their real-world environment [6].
- Virtual reality (VR): In VR, users are completely immersed in a computer-generated environment that can simulate various sensory experiences. VR typically involves the use of head-mounted displays and other input devices to provide a sense of presence within the virtual environment [7]. Prominent examples are the HTC Vive and the Meta Quest.
- Augmented virtuality (AV): This term is less commonly used than the others. It refers to scenarios where real-world elements are brought into a virtual environment. For example, capturing real objects or people and placing them into a virtual space. The Varjo XR-3 is capable of providing such a function and is able to make a video stream into the virtual world (VR). A concrete example could be showing a video stream of the (real) smartphone in VR, so the user can answer a text message without actually leaving VR (removing the headset and thus breaking the illusion being in "another world," the simulated virtual environment).

Diminished Reality

What is often overlooked in this concept is the act of *diminishing* real objects (or persons, animals, etc) from reality, rather than *augmenting* the reality with virtual things [8,9]. An introduction to the topic can be found in Cheng et al [10]. A reason for this is that diminishing something from reality needs, in general, a sophisticated understanding of the real scene or environment to make the *diminishing* aspect convincing. In AR, the real world is *just* overwritten with a virtual object. In diminished reality (DR), however, the real-world part that is *augmented* or *diminished* needs to seemingly *fit* to the reality around it. In addition, this should all be performed in real time when a user is walking around the real world, and an algorithm has to do the following (note that the first 3 items are part of the Extent of World Knowledge axis of the taxonomy by Milgram and Kishino [1]):

- Detect and track the real object that has to be removed or diminished;
- Perform geometric modeling of the scene and objects to be added or subtracted (preexisting or captured once or in real time);
- Apply the lighting model of the scene to objects added or to part of the revealed scene when something is removed (preexisting or captured once or in real time); and then
- Combine all the previous points together as the scene description for the rendering algorithm.

All of this has to be done not only in real time but also with very high precision. The inserted virtual object has to fit seamlessly into and make sense with the reality; minor

discrepancies will appear to be a glitch and will be noticed immediately by the user, as we recently observed in a DR user study [11]. In fact, we think that diminution and augmentation require fundamentally different technologies. In our opinion, an augmentation may be needed to alter reality at a certain position with regard to other (real) objects (eg, displaying a patient's tumor as an AR hologram on the patient in front of you, at the real position, such as for needle guidance [12]), but no seamless and semantic fitting is necessary. As soon as a virtual object needs to fit into the scene semantically, we consider this to require diminution. Hence, for augmentation, you *only* need a volume rendering process with some basic options, such as position, size, and transparency. For diminution, however, additional fundamentally different technologies are needed. The scene has to be analyzed and *understood*, and a meaningful replacement has to be generated and *inserted* as an AR hologram. An example could be glasses that are *removed* from a person in front of you.

In summary, the user has to get the impression that the real, diminished object does not exist at all in reality [13]. Besides sophisticated algorithms, this course of action needs a considerable amount of computing power. Fortunately, there has been tremendous progress in both areas during the last years, with deep learning-based approaches and GPUs that can run these kinds of algorithms, even in real time. As a result, DR has already found its way into some applications [5], such as virtual furniture removal for redecorating purposes (eg, IKEA Kreativ [14]). Other possible applications for DR include the following:

- Privacy enhancing: In a live video feed, certain objects or information can be blurred or removed in real time to protect sensitive or private data.
- Training and education: DR can be used to remove distractions in a learning environment or highlight specific items to focus on.
- Therapeutic applications: For someone with a phobia of spiders, a DR system could recognize spiders in the person's field of view and diminish or replace them with less threatening images to reduce anxiety. Additionally, sensory overload, a feature of autism, could be diminished with a DR system, to reduce overstimulation.

Directional and Layer-Based Taxonomy

Nevertheless, for all these aforementioned reasons, we think that DR needs to be more prominent on the RV continuum, as shown in [Figure 1 \[15\]](#), without delving deeper into the broad topics of mediated reality [9] or even multimediated reality [16]. This will not only assist in the decision-making for hardware (devices) and software that are needed for new DR applications but also help unfamiliar users to get a better understanding of the entire extended reality (XR) topic (note that we are addressing this revision to the continuum purely from an application or user point of view [POV], not from the POV of an MR researcher or engineer). An example application for DR could be the real-time anonymization of a face via XR. There is a huge difference if a device detects the eye area and *simply*

inpaints a black bar over the eyes (without considering the surrounding facial area) or inpaints the eyes with *different* or *meaningful* ones that fit perfectly to the surrounding facial area. The black bar approach can probably be performed on a current smartphone, whereas the second approach needs much more sophisticated hardware and computing power, with an integrated GPU that can run a trained, deep inpainting neural network in real time (note that a user with an XR headset would move around in general, which also changes the POV on the face to be anonymized, so the inpainting algorithms also has to be executed continuously in real time). In this context, we also think that the upcoming Apple Vision Pro will push the limits in DR, because it is a video-see-through device that can enable DR to reach its full potential [17]. In fact, the *Digital Crown* hardware of the Apple Vision Pro, which also exists for the Apple Watch, should enable us to seamlessly *walk* along the whole RV continuum (back and forth) and bring medical DR applications to reality, which are still almost nonexistent currently [18]. A potential example of the photo-editing capabilities of newer cell phones as a diminution operation is shown in [Figure 2 \[15\]](#). In this medical example, DR enables the *removal* of a skin tumor virtually from a patient's face before surgery.

Diminished virtuality (DV), however, remains a curiosity, and not even ChatGPT—which has been fed with 300 billion words from books, web texts, Wikipedia, articles, etc [4]—can handle this term as of January 2024 ([Textbox 2](#); the original ChatGPT transcript is shown in [Multimedia Appendix 2 \[3\]](#)).

Figure 1. An updated reality-virtuality continuum where “diminishing” is more prominent to ensure a better understanding. The figure shows a real operation room (OR), which is “real” in the two left columns and computer-generated in the two right columns. In “reality,” a real physician is standing inside an OR without any computer-generated objects. In “augmented reality,” the real physician wears extended reality (XR) glasses in the OR and looks at a computer-generated skull of the patient to be treated. In “augmented-diminished reality,” the real OR table has been removed (but also note that the computer-generated skull is not visualized). On the right side is “virtuality,” that is, virtual reality (VR), where a computer-generated OR with a table and a skull are shown in VR (to a user wearing VR glasses). In “augmented virtuality,” the real physician is shown inside the VR OR. In “augmented-diminished virtuality” (ie, mediated virtuality), the computer-generated OR table is removed, but note that the real physician is still shown. In “diminished virtuality,” the OR table has been removed, but the real physician is also not shown. The “augmenting-diminishing” continuum shows the degree of augmentation and diminution (note that this does not apply for “reality” and “virtuality”). Scenarios where a diminution happens belong to “disrupted reality.” The images within the figure were generated by DALL-E 3 (OpenAI) [15] and then further modified by the authors.

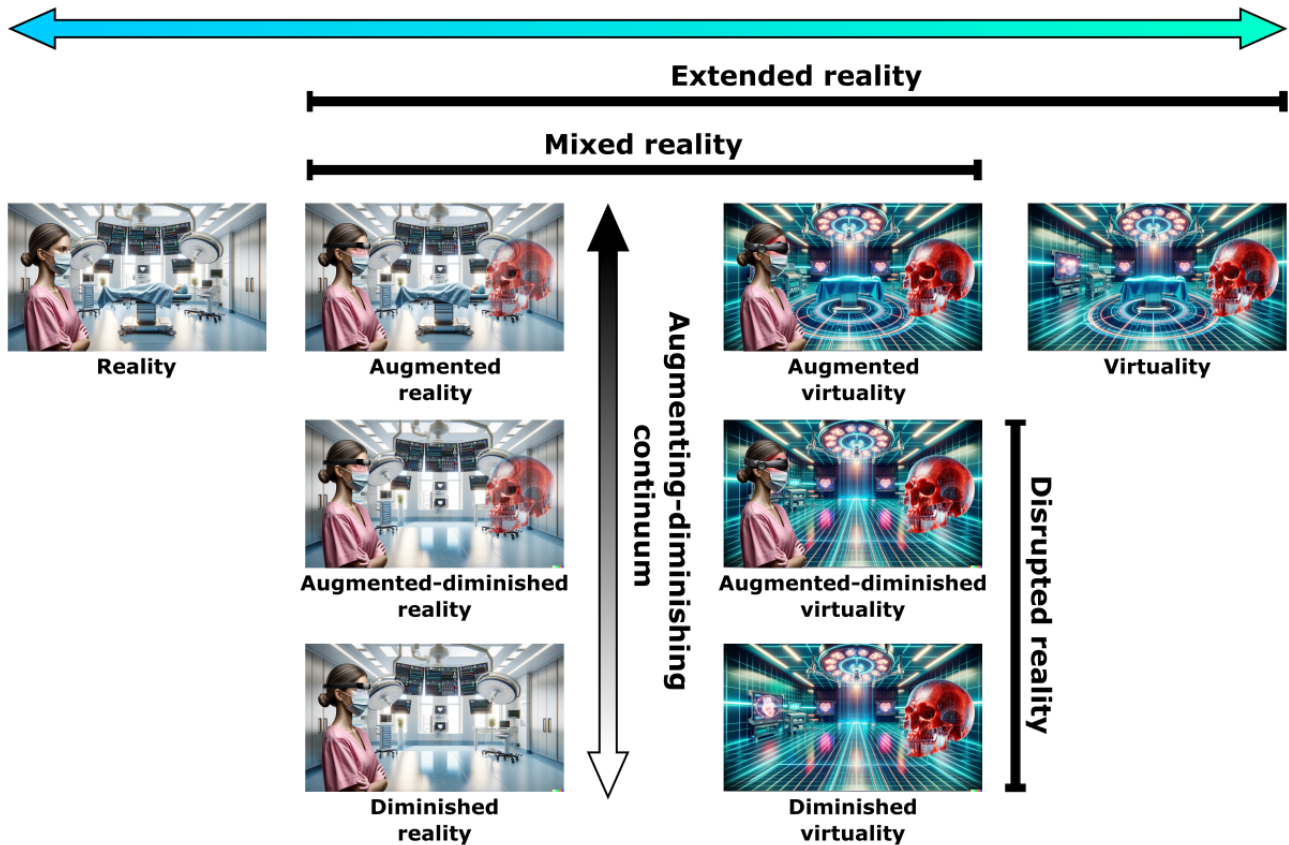


Figure 2. An example of the photo-editing capabilities of newer cell phones as a diminution operation, enabling the “removal” of a skin tumor virtually from a patient’s face before surgery. This figure was generated by DALL-E 3 (OpenAI) [15] and then further modified by the authors.



Textbox 2. Asking ChatGPT about “Diminished Virtuality” (as of January 2024).

ChatGPT prompt:

- What is “Diminished Virtuality”?

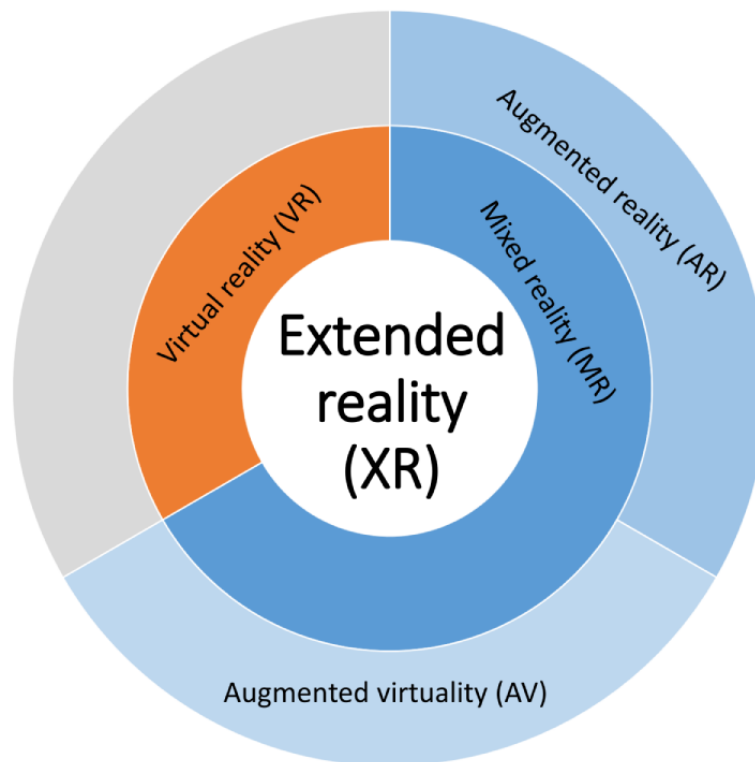
ChatGPT output:

- “Diminished Virtuality” is not a widely recognized term or concept as of my last knowledge update in January 2022. It’s possible that this term has been coined or introduced in a specific context or field after that date, or it may be a term used in a niche or specialized area that is not widely known.
- If you have more context or information about where you came across this term or its usage, I would be happy to try to provide more information or insight based on that context.

DV can perhaps be best imagined as starting on the extreme right side on the RV continuum, which contains only virtual objects (virtual environment and VR), and going along the continuum toward the left to reach diminished virtual elements (see the figure of the RV continuum by Iriqat and Vatansever [19], and note that this is especially of interest for computer-generated structures that are very complex and where only some parts need to be diminished). This should be possible with the *Digital Crown* hardware of the Apple Vision Pro: when fully immersed, the virtuality is reduced to make the real world partly visible. Apple describes scenarios where people might want to increase the pass-through when they intend to interact with a nearby physical object or read text on another device. Another real-world scenario could be a so-called tumor board meeting that is held in VR, where several experts from around the world gather to discuss a rare case and certain virtual elements (images, texts, etc) are diminished because of privacy issues (note that the mixture of reality here is also modifiable): an externally tuned-in expert (who is traveling) can see certain patient information because he or she belongs to the clinic where the patient is located, whereas another externally tuned-in expert who does not belong to the clinic of the patient should not see or hear certain patient information. However, the full potential of DV would unfold when the virtuality is diminished in a way that also fits with the upcoming reality. An example would be a real-world person showing up in VR between virtual objects. Imagine layers of virtual and real context stacked up but still seamlessly interplay with each other for the final output. In fact,

this layer-based concept could also extend to mediated and even multimeditated realities, where, for example, different sounds (real and virtual) interplay with each other, depending on their location and *depth*. “Enaudio” (the “hearing” equivalent to envision) hearing real rain outside in the real world that are mixed with virtual sounds while inside a virtual room. Real and virtual input from different senses could also be mixed; for example, there is a (virtual) hole in the VR room and the (real) rain falls inside this virtual room, generating simulated sounds as they hit virtual objects in the VR room. The same also works for outputs and their combinations; for example, the real voice from someone wearing the headset is mixed with virtual sounds, or real smells are mixed into VR by generating the corresponding virtual objects there. Finally, some could argue whether the RV continuum really ends on *one side* with physical reality [20], because the brain creates reality—comparable to a head-mounted display creating VR—but does not detect it. This could be discussed and explored by the community in the future, and in this regard, we want to propose a diagram of XR that loops back (as opposed to a continuum on a straight line with 2 ends) as an inspiration (Figure 3). In summary, XR is a niche yet growing topic, because more and more consumer devices with better hardware have become available during the last few years. In parallel, artificial intelligence (AI)-based algorithms have made 1 breakthrough after another, which can, for example, be explored to develop novel applications for an intelligent health care metaverse [21].

Figure 3. The extended reality (XR) continuum with its subsections (virtual reality [VR], mixed reality [MR], augmented reality [AR], and augmented virtuality [AV]) folded in an outside-in fashion with a circular representation.



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Conflicts of Interest

BP is an associate editor of the *Journal of Medical Internet Research*. The other authors have no conflicts of interest to declare.

Multimedia Appendix 1

Asking ChatGPT about "the reality-virtuality continuum."

[[PNG File , 303 KB - xr_v1i1e52904_app1.png](#)]

Multimedia Appendix 2

Asking ChatGPT about "diminished virtuality."

[[PNG File , 212 KB - xr_v1i1e52904_app2.png](#)]

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Abbreviations

- AI:** artificial intelligence
- AR:** augmented reality
- AV:** augmented virtuality
- DR:** diminished reality
- DV:** diminished virtuality
- MR:** mixed reality
- POV:** point of view
- RV:** reality-virtuality
- VR:** virtual reality
- XR:** extended reality

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Cybersecurity and Privacy Issues in Extended Reality Health Care Applications: Scoping Review

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Abstract

Background: Virtual reality (VR) is a type of extended reality (XR) technology that is seeing increasing adoption in health care. There is robust evidence articulating how consumer-grade VR presents significant cybersecurity and privacy risks due to the often ubiquitous and wide range of data collection and user monitoring, as well as the unique user impact of attacks due to the immersive nature of the technology. However, little is known about how these risks translate in the use of VR systems in health care settings.

Objective: The objective of this scoping review is to identify potential cybersecurity risks associated with clinical XR systems, with a focus on VR, and potential mitigations for them.

Methods: The scoping review followed the PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews), and publications were reviewed using Covidence software. The Google Scholar database was searched using the predefined search terms. The inclusion criteria of the articles were restricted to relevant primary studies published from 2017 to 2024. Furthermore, reviews, abstracts, viewpoints, opinion pieces, and low-quality studies were excluded. Additionally, data on publication statistics, topic, technology, cyber threats, and risk mitigation were extracted. These data were synthesized and analyzed using the STRIDE (spoofing, tampering, repudiation, information disclosure, denial of service, and elevation of privilege) framework, enterprise risk management framework, and National Institute of Standards and Technology Cybersecurity Framework, as well as developing threat taxonomies.

Results: Google Scholar returned 482 articles that matched the search criteria. After title and abstract screening, 53 studies were extracted for a full-text review, of which 29 were included for analysis. Of these, the majority were published in the last 4 years and had a focus on VR. The greatest cyber threat identified to XR components was information disclosure followed by tampering when mapped against the STRIDE framework. The majority of risk mitigation strategies provide confidentiality and integrity and can potentially address these threats. Only 3 of 29 papers mention XR in the context of health care and none of the identified threats or mitigations have been studied in a clinical setting.

Conclusions: This scoping review identified privacy threats where personal and health-related data may be inferred from VR usage data, potentially breaching confidentiality, as the most significant threat posited for health care VR systems. Additionally, immersive manipulation threats were highlighted, which could potentially risk user safety when launched from a compromised VR system. Many potential mitigations were identified for these threats, but these mitigations must first be assessed for their effectiveness and suitability for health care services. Furthermore, health care services should consider the usage and governance of XR for each individual application based on risk threshold and perceived benefits. Finally, it is also important to note that this scoping review was limited by the quality and scope of the studies returned by Google Scholar.

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KEYWORDS

cyberattacks; cyber defence; cyber security; extended reality; health care; privacy; risk mitigation; virtual reality; cybersecurity

Introduction

Background

Extended reality (XR) is a broad term used to refer to augmented reality (AR), virtual reality (VR), and mixed reality (MR), or a technology that combines the use of them. These technologies are defined by their ability to extend the physical world with a virtual world to varying degrees depending on the specific type of XR technology [1]. AR enhances the physical world by overlaying virtual features and functionality, whereas VR immerses the user in a distinct virtual world, often through a head-mounted display (HMD) [2]. Moreover, audio output is also usually present, and together these sensory features immerse the user in a virtual world through visual and audio cues. MR is midway between VR and AR, in which the overlaid virtual world coexists and interacts with the physical one [3]. Each technology provides a new paradigm of human-computer interaction and is designed to improve quality of life, either through entertainment or application in industry and the workplace. A growing area of VR applications is health care [4].

One example of VR applications within health care is in the area of occupational therapy, which aims to improve patients' quality of independent living through activities and exercises targeting specific movements and functions [5]. Current methods in occupational therapy use different technological resources, such as mechanical setups that emulate real-life activities [6]. Technology-based tools such as video games and sensor-based technologies are also used in clinical practice [7]. Among the XR-based therapy methods, VR systems have shown an increasing demand and have started to be used as an adjunct to conventional therapy [8-10].

However, XR-based health care interventions have cybersecurity and privacy risks. These types of interventions often rely on multiple sensors as input modalities. Many of these sensors (such as eye tracking, microphones, cameras, hand tracking, and motion tracking) are inherent to HMDs and have multiple software components. These components generate an enormous amount of data on a user, which is required to create an immersive experience. However, this monitoring also creates the potential for significant privacy violations if these data are mishandled. When combined with data processing and artificial intelligence (AI) and machine learning (ML) models, this data can be used to identify, deanonymize, and profile users. It has been demonstrated that 100 seconds of VR motion is sufficient to identify a user within a pool of over 50,000 individuals with 94.33% accuracy [11]. A user's height, wingspan, age, gender, country of origin, and mental and physical disability status are just some additional characteristics that can be inferred from this data [12].

On top of these privacy issues, XR and VR devices are vulnerable to conventional passive and active cybersecurity attacks and threats, including eavesdropping attacks, man-in-the-middle attacks, and denial-of-service (DoS) attacks

[13]. These threats can disclose private data or render the XR device unusable. Another type of cyberattack specific to VR includes attacks that target the unique features of an immersive session. They are called immersive attacks and have the potential to cause physical and psychological discomfort or even harm by tampering with the output of the device. For example, they may trick a user into colliding with a real-world object in a chaperone attack by manipulating the display [13], potentially causing the user to fall and injure themselves, or they may display triggering content in an overlay attack [13]. Additionally, cybersickness is a visually induced side effect that can be triggered by these attacks [14]. Thus, the attacks described have been demonstrated in a general experimental setup [13] to have the potential of impacting user well-being by compromising the VR devices.

As XR technology develops, the extent of user tracking and data collection will likely expand and place user security and privacy at further risk (particularly their biometric data). There are 5 categories of countermeasures for these risks that can be found in the literature [3]. They are input protection, data protection, output protection, user interaction protection, and device protection. Despite these countermeasures, no comprehensive mitigating tool exists to protect users from cyberattacks [12].

Although a large and growing body of research exists on the topic of security and privacy issues for XR systems, the specific cybersecurity challenges, risks, and mitigations for XR or VR health care services are underexplored. Most related work is on the risks of integrating Meta [15] XR technologies and ecosystems with health care systems and infrastructure. Meta, formerly known as Facebook, is a company that produces the Meta Quest line of HMDs. They are also responsible for the Metaverse, an XR platform capable of integrating with a range of digital devices and providing multiple use cases and applications, the primary one being social [16]. The key health care services provided by the Metaverse are ubiquitous health monitoring, distributed medical AI, and virtual therapy through gamification and social activities. These services will likely have issues maintaining the privacy and security of user data at rest and in transit over the internet. There is the potential of private and identifying individual data being exposed by AI and ML trained on this data. In addition, gamification exposes a new vector where individuals can be invasively monitored, both by other users in social situations and malicious actors [17]. When the data being gathered and observed is generated from usage in health care services, this can potentially disclose health and biometric information about the user [17,18]. Secure computation techniques such as blockchain are recommended to maintain the integrity and confidentiality of data, along with legal protection of Metaverse-collected data through legislation such as the Health Insurance Portability and Accountability Act in the United States [19]. Although the Metaverse is a growing XR platform, XR technologies are not limited to it.

Apart from Meta, concerns have been raised about the challenges to user privacy rights that come with VR usage in health care. Users can potentially be identified by the extensive data collected by HMD sensors, which might be shared with social media platforms and other parties, like the manufacturers of the device (eg, Meta). This creates technical and ethical challenges for clinical adoption [20]. There is potential danger in using wearable sensors and HMDs due to the amount and type of data generated by them in a clinical scenario, so some health care organizations may not be prepared for the ethical and legal implications [21]. Lakshminarayan et al [22] identified AR and VR technologies as integral to an intelligent, equitable health care system, but these are technologies that can pose significant security and privacy challenges. It is recommended that these be combined with edge computing, wherein computing resources are placed closer to the network to limit transit over the internet.

The existence of cybersecurity and privacy risks of using VR technology in a clinical context has been acknowledged in the literature. However, the specific risks and feasible strategies to mitigate them have not been clearly established. Hence, the potential challenges and consequences of using XR and VR technologies in health care must be understood before widespread clinical adoption to minimize risks to users.

Objectives

A scoping review was conducted to answer the following two research questions:

- Research question 1 (RQ1): What cybersecurity and privacy risks are there to XR components, in particular VR?
- Research question 2 (RQ2): How can cybersecurity risks to clinical XR systems, in particular VR systems, be reduced?

To determine the potential cybersecurity risks and mitigations for a health care VR system, the cyber threat landscape of XR was first established through RQ1. There are overlaps between different XR technologies in terms of cybersecurity and privacy issues and mitigations, so the investigation was not limited to only VR. Risks applicable to VR components were analyzed and summarized to answer RQ1 by developing taxonomies and using established frameworks to classify and organize XR threats.

To use a VR system in a health care setting, the potential cybersecurity risks and requirements must be understood. RQ2 systematically identifies and analyzes risk mitigation strategies and technologies for the risks established in RQ1, with a focus

on risks that uniquely impact XR and VR systems in a health care setting. The results of this scoping review are intended to be used to inform risk management for health care organizations looking to implement XR technology and potential future directions for the secure development of VR tools for use in health care.

Methods

Overview

This review was conducted using the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) checklist (Checklist 1) [23]. Considering the large amount of VR technologies and platforms, VR studies that were not relevant to the HMD platform were excluded. Most literature on the topic of XR cybersecurity and privacy was published after 2017 [24,25]. Additionally, two of the most popular VR devices today, the Meta (formerly Oculus) and HTC Vive line of HMDs, were not released for the public until 2016 [26]. As such, 2017 was chosen as the cutoff year, and any studies published before then were excluded to keep results relevant. Reviews, abstracts, viewpoints, and opinion pieces were excluded, as well as studies where the cyber threats or countermeasures were not relevant to XR or were poorly described. Low-quality studies, including those that have not been peer reviewed, were also excluded. Due to the large number of studies returned by the search terms, the objective was to reduce this to a smaller number of high-quality, relevant primary studies. The full search strategy development and process can be found in Multimedia Appendix 1.

Database

All literature was found using Google Scholar. Google Scholar is a search engine that indexes content from a range of scholarly sources and databases including the Association for Computing Machinery and Institute of Electrical and Electronics Engineers, as well as medical literature repositories such as PubMed. Due to the research topic's intersection between different disciplines including computer and medical science, Google Scholar is an effective electronic database to view literature results. This mitigates the risk of missing important literature. Results were refined using the search terms and date range criteria.

Search Strategy

Google Scholar was searched (one author, KL) from January 1, 2017, to January 1, 2024, using the predefined terms identified in Table 1.

Table 1. Google Scholar search term strategy.

| Search query | Justification |
|--|--|
| (privacy OR security OR attack OR threat OR secure OR securing) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | Query for privacy and cybersecurity issues in extended reality and related technologies independent of their application |
| (access control OR side-channel OR user profiling OR tracking user location OR dark designs) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | Query for concerns adjacent to privacy and cybersecurity issues independent of their application |
| (survey architectures OR analysis healthcare) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | Query for the use of extended reality and related technologies in health care and nonstandard architectures |

The publications returned by this search were screened by title and abstract and for removal of duplicates independently by one author (KL). A full-text review was facilitated by the Covidence research review management software (Veritas Health Innovation [27]) and conducted independently by 3 authors (KL, MD, and AMK) against the inclusion and exclusion criteria. Conflicts were resolved by all authors through discussion and then agreement.

All of the following criteria must be met for a study to be included: (1) publication year is between 2017 and 2024, (2) the issue or mitigation described in the study is relevant and applicable to XR and is well described, and (3) the terms of the search request appear in the title of the study as specified in the full search strategy.

The criteria for a study to be excluded are as follows. Only one of the following criteria must be met for a study to be excluded: (1) the publication date is before 2017, (2) the study is a literature survey, viewpoint piece, or opinion piece, (3) the issue or mitigation described in the study is not relevant or applicable to XR or is poorly described, (4) the study is not peer reviewed, and (5) the study is on VR but is not relevant to the HMD platform.

Data Synthesis

The complete description of extracted information and the data charting process can be found in [Multimedia Appendix 1](#). Data charting was conducted by one author (KL) into tables using Google Sheets. Disagreements were resolved by discussion, and consensus was reached. The following data were extracted

from each included publication: (1) publication information (author and year of publication); (2) topical information (XR domain and topic classification); (3) cyber threat information (cyberattacks identified, attack privilege level and components investigated); and (4) risk mitigation information (defense technologies and risk mitigation strategies identified).

Authors were not contacted to obtain missing data. The complete data extraction template can be found in [Multimedia Appendix 1](#). We used 4 strategies to synthesize and interpret this data: (1) STRIDE threat modelling framework [28] for cyber threat and mitigation analysis, (2) taxonomic summarization of security and privacy issues, (3) enterprise risk management (ERM) [29] mapping of health care concerns, and (4) the National Institute of Standards and Technology (NIST) Cybersecurity Framework [30] for classification of mitigation strategies and technologies.

Cyber threats were categorized using the STRIDE model, which is a common cyber threat modeling framework developed by Microsoft to enable the organization and analysis of cyber threats. STRIDE defines 6 categories of cyber threats: spoofing, tampering, repudiation, information disclosure, DoS, and elevation of privilege [28]. Each threat is explained in [Table 2](#). The threats and cyberattacks extracted from the included publications, if not already categorized by STRIDE, can be given a categorization according to these definitions. Furthermore, the STRIDE framework was used to map mitigating technologies to threats. Each STRIDE threat type is mitigated by the attribute stated in [Table 2](#), and thus mitigations can be classified by the mitigating function they provide.

Table . STRIDE threat definitions and associated mitigation [28].

| STRIDE threat | Definition | Mitigation |
|------------------------|---|------------------|
| Spoofing | Impersonation of other processes, entities, or people can lead to illegitimate access to a system | Authenticity |
| Tampering | The system can be modified or broken to an adversary's benefit | Integrity |
| Repudiation | Actions taken by an adversary in or against the system cannot be traced back to the adversary | Nonrepudiability |
| Information disclosure | Protected or private information can be disclosed by or to the adversary | Confidentiality |
| Denial of service | Authentic and permitted users are unable to use the system | Availability |
| Elevation of privilege | An adversary can illegitimately increase their access to the system | Authorization |

Threat taxonomies were developed by manually reviewing each XR-specific cyberattack and organizing them hierarchically based on the following attributes:

1. Security versus privacy: security threats are those that involve an explicit intrusion, modification, or breaking of the system for illicit purposes, while a privacy threat involves data collection with minimal to no illicit intrusion into the system, usually for the purposes of data disclosure.
2. Unique XR feature exploited: the specific XR feature exploited by each threat was identified. These features could include but were not limited to immersive design,

communication channels, side channels, and data collection capabilities.

3. Threat target (optional): these threats could be further delineated based on their intended effect, such as manipulation of the user, or intended target, such as the privilege level that the attack targets.

The NIST Cybersecurity Framework is comprised of 5 core functions for organizations to address their cybersecurity measures: identify, protect, detect, respond, and recover [30]. Each function is summarized in [Table 3](#). This framework enables the authors to communicate how and where a mitigation or

countermeasure can potentially improve the XR cybersecurity posture of a health care organization. Each mitigation extracted from the included publication can be mapped to a function given the definition.

Table . National Institute of Standards and Technology cybersecurity framework functions and definitions [30].

| Framework function | Definition |
|--------------------|--|
| Identify | Includes cataloging and understanding the assets, business environment, and risks to the organization, as well as implementing policies and procedures for maintaining cybersecurity |
| Protect | Regards implementing technical and strategic mitigation strategies to prevent and lower the likelihood and impact of a cyber incident, which may involve implementing access control, awareness and training, and maintaining infrastructure |
| Detect | Involves implementing technologies and strategies to detect when a cyber incident occurs, which may include implementing continuous monitoring software on assets and detection procedures |
| Respond | Involves implementing technologies and strategies to respond to a cyber incident, which may include implementing incident response plans and cyber forensic capabilities |
| Recover | Regards implementing and strengthening recovery ability during or after a cyber incident has occurred, which may include incorporating lessons learned from the incident into policies and procedures and implementing recovery procedures |

While the NIST Cybersecurity Framework is effective for communicating mitigations, an ERM framework is effective for articulating and organizing risks to an organization, in this case a health care organization. To this end, 5 categories were selected to articulate organizational risks presented by cyber threats to a health care organization looking at implementing clinical XR systems: compliance with applicable regulatory measures; ability and capacity to deliver health services; confidence of the community and stakeholders in the health care organization; financial performance; and workplace health

and safety. Potentially significant risks posed by the threats and cyberattacks identified in the data extraction can be summarized for each category.

Results

Search Results

The results of each stage of the search process are summarized in [Figure 1](#). [Table 4](#) summarizes the total number of papers collected and excluded.

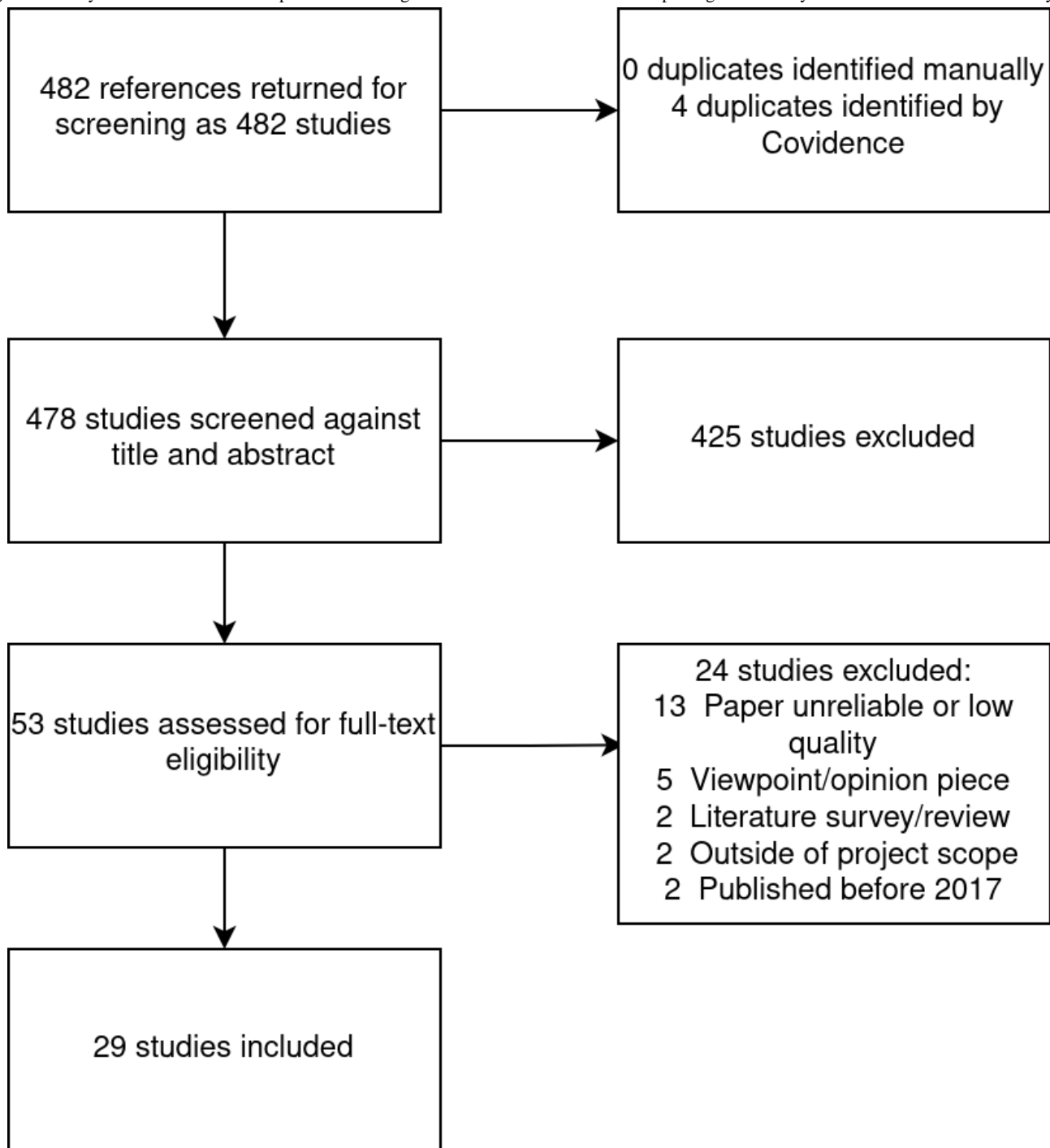
Figure 1. Study extraction and selection process following PRISMA. PRISMA: Preferred Reporting Items for Systematic reviews and Meta-Analyses.

Table . Study collection and exclusion process summary.

| | Number of studies |
|--|-------------------|
| Search terms used to collect studies | |
| (privacy OR security OR attack OR threat OR secure OR securing) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | 451 |
| (access control OR side-channel OR user profiling OR tracking user location OR dark designs) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | 13 |
| (survey architectures OR analysis healthcare) AND (Virtual reality OR augmented reality OR mixed reality OR extended reality) | 18 |
| Reasons for study exclusion | |
| Abstract screening | 425 |
| Paper unreliable or low quality | 13 |
| Viewpoint/opinion piece | 5 |
| Literature survey/review | 2 |
| Outside of project scope | 2 |
| Published before 2017 | 2 |

Study Characteristics

Publication Statistics

The literature search was restricted to studies published between 2017 and 2024. A total of 482 articles were initially retrieved from the database, and 29 studies were included in the final analysis [31-59] (Multimedia Appendix 2). The publication year distribution can be seen in Multimedia Appendix 3. Most studies found were published in 2023 (10 papers), followed by 2020 (5 papers). Approximately 83% (24/29) of the papers were published in the past 4 years.

XR Technologies

The studies were organized according to the XR technology in their title, which could be either VR or any other XR technology (such as AR or MR). A total of 16 studies focused on VR, while the remaining 18 were concerned with other XR technologies. All papers specified the dimension in the title except two works:

[59] and [32]. Wang et al [59] was classified as other XR since the study focused on the Metaverse and the paper by Letafati and Otoum [32] was classified as VR. A paper could focus on more than one dimension and so could be counted more than once. A significant number of papers focused on VR (16 papers), but most focused on other XR technologies (18 papers).

Cybersecurity Focus

The studies were classified by the contribution they made to the field of cybersecurity and privacy in XR. These contributions were classified as mitigation identified, privacy threat identified, security threat identified, taxonomic analysis, or user experience evaluation. A paper could make more than one contribution and thus have more than one classification. The distribution of contributions can be seen in Table 5. Most papers either identified a mitigation or a privacy threat or both, followed closely by papers that identified a security threat. Taxonomic analyses and user experience investigations were limited to only 5 contributions combined.

Table . Count of papers organized by contribution.

| Contribution | Number of papers |
|----------------------------|------------------|
| Mitigation identified | 18 |
| Novel privacy threat | 18 |
| Novel security threat | 13 |
| Taxonomic analysis | 3 |
| User experience evaluation | 2 |

RQ 1: What Cybersecurity and Privacy Risks Are There to XR Components, In Particular VR?

The 29 papers covered every XR domain, with a predominant focus on VR. To identify the cybersecurity and privacy issues of XR systems, data were extracted from these papers, such as XR components investigated as well as cyber threats and attacks

identified. Taxonomies were developed from the survey data extraction to classify and analyze these data. There are many security and privacy risks to XR components, but the scope was limited to only focus on those that are unique to an XR environment in either their method or effect. Definitions for important cybersecurity and computer science terms used in

this section and elsewhere are provided in [Multimedia Appendix 4](#).

A classification of XR component types can be seen in [Figure 2](#), where components are broadly classified as either device, communication, or storage. Common components can be seen in yellow and are not limited to the ones shown. The XR proof-of-concept devices for experimental studies that identified either a security or privacy threat or a mitigation strategy for

those devices were counted. Many studies used more than one proof-of-concept device type. Of the devices, 28 were XR HMD devices or other head-mounted eyewear (28/31), with many using the HTC Vive (8/31). However, most papers used a variety of other devices that were only used within one study, and two studies used a mobile phone device, the only non-HMD device. A summary of devices used can be seen in [Table 6](#). All components tested and investigated for threats were thus user device components.

Figure 2. Classification of extended reality component types. HMD: head-mounted display.

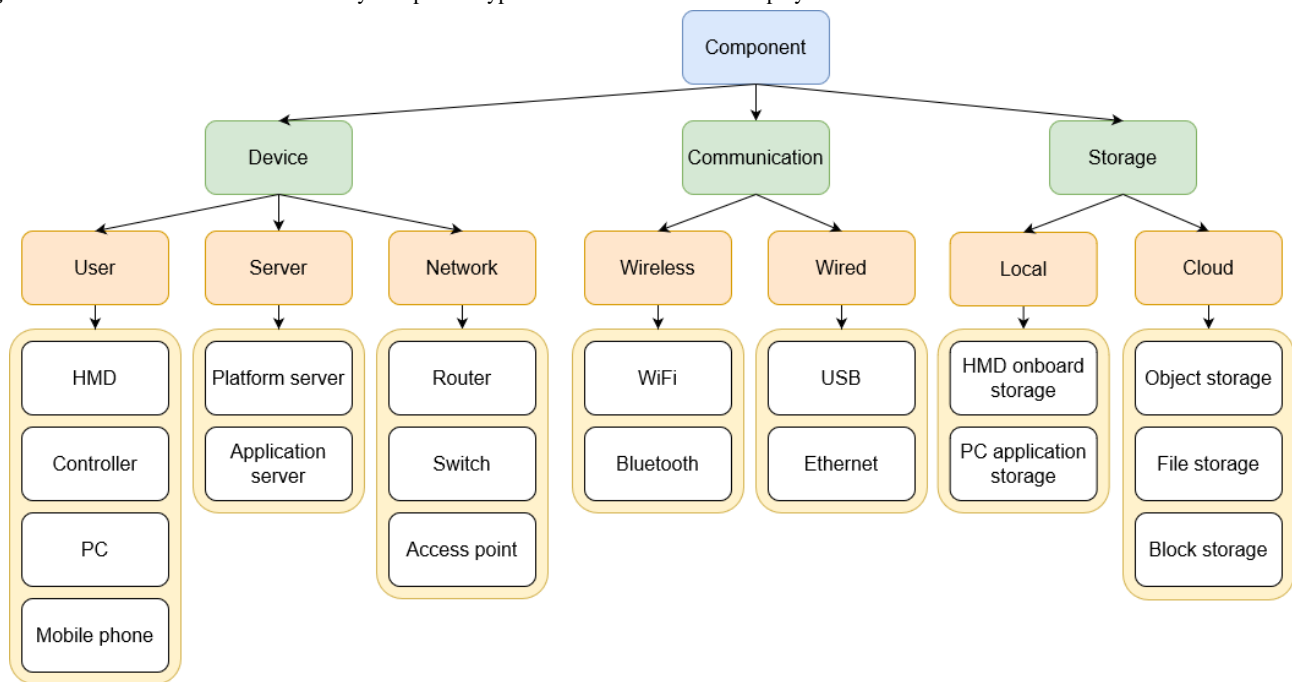
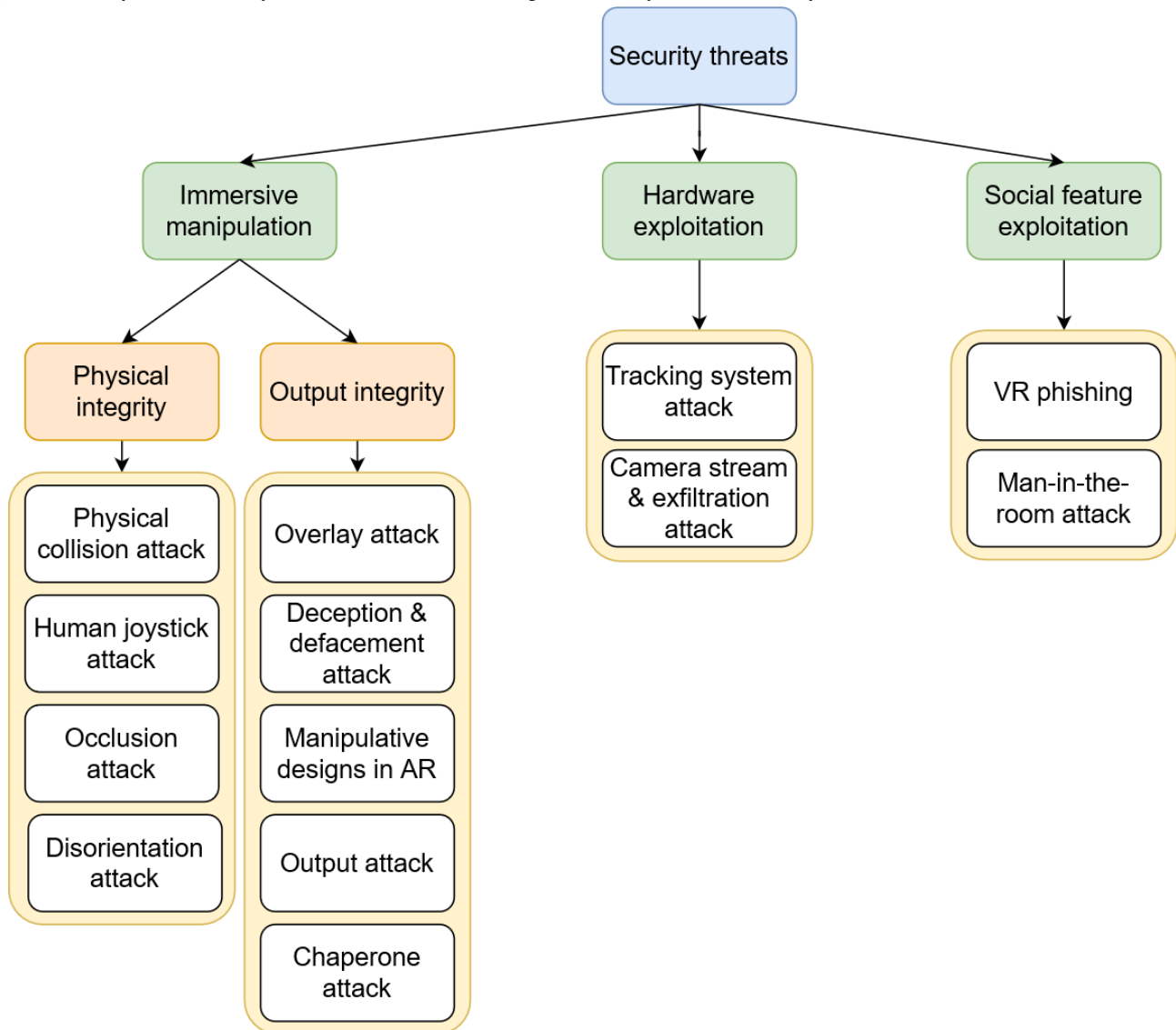


Table . Proof-of-concept device usage count across studies.

| Proof-of-concept device | Number of papers |
|-------------------------|------------------|
| Oculus Rift | 3 |
| Meta Quest | 5 |
| Meta Quest 2 | 2 |
| HTC Vive | 7 |
| Samsung Gear | 2 |
| Mobile | 2 |
| Other | 10 |

We identified 20 unique attacks specific to an XR domain, as can be seen in the attack catalog in [Multimedia Appendix 5](#). The security threat taxonomy and attacks classified in [Figure 3](#) were developed from the literature review and by analyzing these attacks as described in Methods. Security threats specific to XR components are those that involve an explicit tampering, intrusion, or breakage of the system. They can be broadly

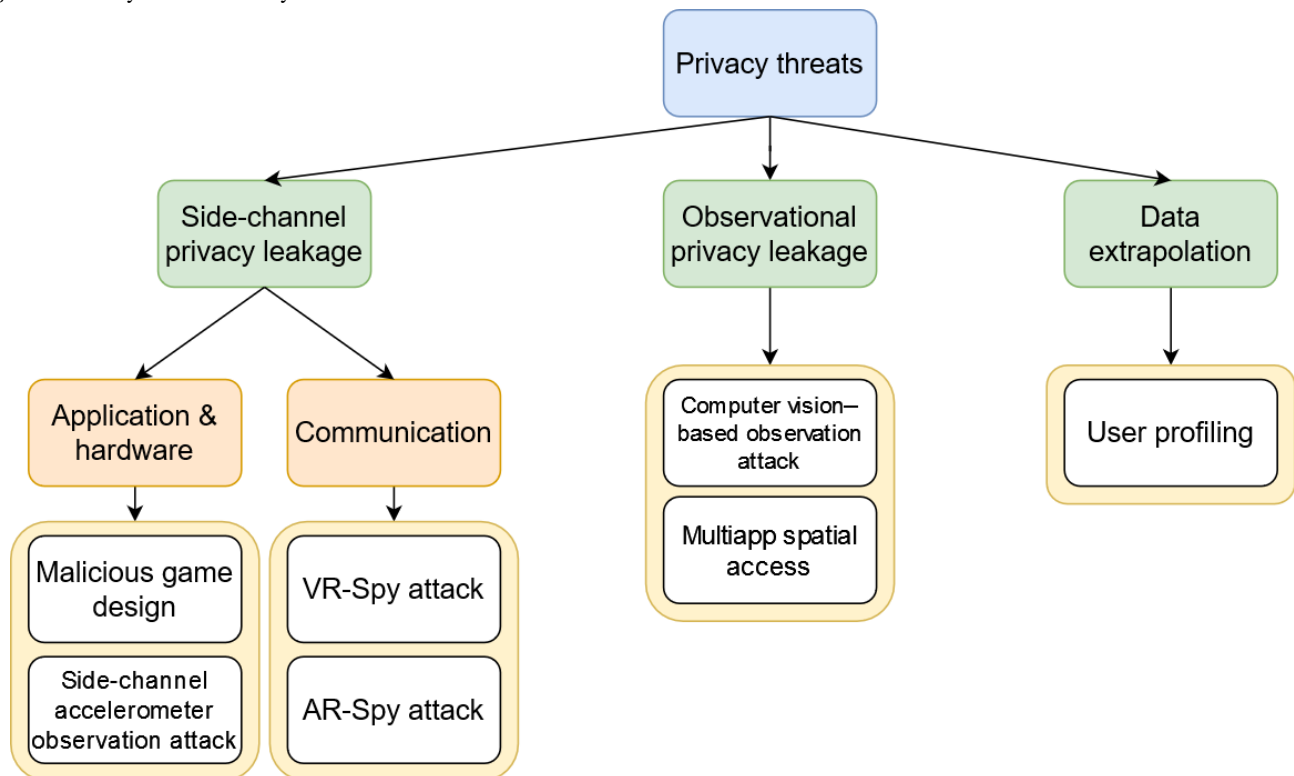
classified as immersive manipulation, hardware exploitation, or social feature exploitation. Hardware exploitation encompasses any threat or attack that targets the unique hardware features of an XR system to degrade or intrude. Social feature exploitation includes any threat or attack that targets the unique social features of an XR system.

Figure 3. Security threat taxonomy and associated attacks. AR: augmented reality; VR: virtual reality.

Immersive manipulation constitutes the majority of threats and cyberattacks identified in the literature. This encompasses any threat that utilizes the unique features of an XR session to target the security of the system or safety of the user. Threats that target physical integrity are those that aim to physically manipulate or impact a user, such as by causing cybersickness and physical collision with real-world objects [33,34]. Threats that target output integrity include any threats aiming to impact or degrade the sensory features of an immersive session. They include deception and defacement attacks, which were found to have the potential to impact users' mental and emotional well-being by outputting inappropriate or upsetting visual or audio content [33,35].

The privacy threat taxonomy and associated attacks seen in Figure 4 were developed from the literature review as described

in Methods. Privacy threats to XR components are those that are intended to passively disclose information with limited to no tampering or breaking of the system. They can be broadly classified as side-channel privacy leakage, observational privacy leakage, or data extrapolation. Privacy leakage refers to any confidential information that is inadvertently leaked and not obtained through an intrusion or premeditated attack on a system. Side-channel privacy leakage refers to privacy leakage that happens as an unintended result of the technical design of the system. This privacy leakage can either happen at the application and hardware level or communication level. Observational privacy leakage encompasses attacks that use physical observation of an XR user, or an XR user observing bystanders and the environment. Data extrapolation includes attacks that infer additional attributes and characteristics of a user, their environment, or a system from collected XR data.

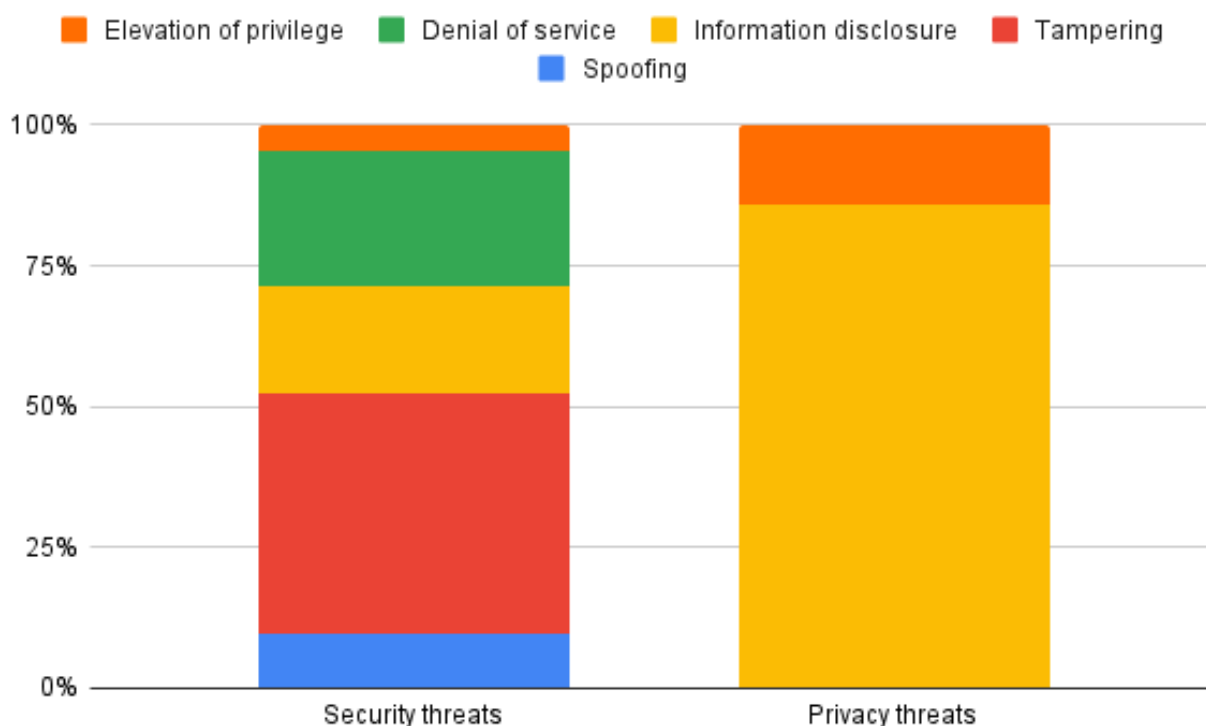
Figure 4. Privacy threat taxonomy and associated attacks.

The type of information that can be collected and inferred about users in these attacks includes biometric data, psychological data, and personally identifiable information such as [35,36] color blindness, mental and physical disability status, physical fitness, mental acuity, eyesight, and visual acuity. The study by Nair et al [36] demonstrated a side-channel privacy leakage attack with a VR game that can inconspicuously harvest such health-related data. A user profiling framework involving data collection and AI models to extrapolate such data was developed by Tricomi et al [37], with high mental workload tasks with eye tracking found to be the most effective combination for data collection. These attacks generally do not require any existing information related to the user to be stored on the device or for there to be a link to their social media account. These privacy attacks only require the data generated by the XR system or

observation of the environment or user while they are using the system.

Cyber threats to XR components or the users of them were also classified in terms of the STRIDE model. A cyberattack can be classified into more than one category in the model. Of these cyberattacks, the most common threat was information disclosure, representing 50% (10/20) of attacks. The second biggest threat was tampering (45%, 9/20) and the smallest threat was repudiation (no attacks).

The constitution of the total number of security and privacy attacks by their STRIDE count can be seen in Figure 5. The majority of security threats are also tampering threats, and the majority of privacy threats are also information disclosure threats.

Figure 5. Constitution of security and privacy threats by STRIDE classification.

Garrido et al [38] and Warin and Reinhardt [39] developed an attacker privilege level classification for VR-specific attacks. A summary of the observable data attributes and data sources for each level can be seen in [Multimedia Appendix 6](#). There are 4 different types of attackers: a hardware-level attacker (privilege attacker I) can access the low-level input and output signals of the HMD device; a client-level attacker (privilege attacker II) operates at an application level and can access the system abstract programming interfaces; a server-level attacker (privilege attacker III) can access or control the application servers; and a user-level attacker (non-privilege attacker) includes any attacker that can access public telemetry of the user in a social application. Of the 20 attacks, the most common level they occur at is the client level (70% of attacks, 14/20), and the least common attacker level is server (10% of attacks, 2/20). Some studies explicitly stated the privilege level of their identified attacks, and those that did not were categorized based on their features.

Only 3 studies described cybersecurity and privacy issues of XR in a health care context [32,40,41]. Letafati and Otoum [32] explored the security and privacy risks and potential mitigations of incorporating health care capabilities into the Metaverse as it relates to patient data flow and processing, distributed health

AI/ML, and patient interaction. They identified the primary challenges with these technologies being maintaining the security of data as it is collected and processed, the privacy of these datasets, and the privacy of users as they are monitored in virtual therapy [32]. The NIST Privacy Framework is a tool for managing risk to an organization and improving governance of data it stores and processes. There are 4 tiers of framework implementation that delineate to what extent controls are in place to mitigate privacy risks, the lowest tier being that an organization is risk-informed but implements no controls to safeguard privacy. Health care organizations often exist at the second tier due to valuing data availability over confidentiality, which means limited mitigations are implemented and user AR data are at a higher risk than necessary [41]. Ara et al [40] also identified data security as being one of the greatest challenges for using AR in health care services.

Cybersecurity and privacy threats to VR systems identified in the threat taxonomies and their potential risk in a health care setting can be seen in [Table 7](#), which maps these threats against an ERM model for managing organizational risk. The likelihood and impact of each risk will be highly dependent on the specific health care context and conditions of use of the VR system.

Table . Enterprise risk management framework mapping of extended reality cybersecurity risks for health care.

| Category | Scope | Risk |
|--------------------------------------|--|---|
| Compliance | Risk to the organization's ability to meet legal and regulatory obligations | <ul style="list-style-type: none"> • An immersive manipulation attack that implicates personal safety or well-being can have legal consequences for the organization • Privacy leakage and data extrapolation attacks can potentially expose or deanonymize user health data stored or collected by the organization • Observational privacy leakage attack can implicate user, clinician, and organization privacy • Lack of awareness of cybersecurity and privacy risks can reduce compliance to cybersecurity policies, which can impact organizational ability to meet legal and regulatory requirements |
| Service delivery and capacity | Risk to organization operations and ability to deliver services | <ul style="list-style-type: none"> • An immersive cyberattack that impacts personal safety or well-being can also impact recovery and rehabilitation • Immersive manipulation or hardware exploitation can render the VR system unusable, requiring a disruptive transition to alternate forms of intervention and treatment, which may not be as effective • The impact of a cyberattack (eg, denial-of-service attack) on a virtual reality system can potentially spread and take down other organization resources, services, and access to health data |
| Community and stakeholder confidence | Risk to community and stakeholder confidence and ability to plan and create policies in relation to them | <ul style="list-style-type: none"> • Cyberattacks can reduce community and stakeholder confidence in organizational ability to protect patients |
| Financial | Risk to financial performance, and how variance to this can impact the organization | <ul style="list-style-type: none"> • Cyberattacks that implicate user privacy, safety, or treatment outcomes (eg, immersive manipulation attacks) can cause significant financial consequences for an organization, for example by reducing hospital funding or through legal events |
| Workplace health and safety | Risk to patients, staff, and the organization from workplace health and safety events | <ul style="list-style-type: none"> • An immersive manipulation cyberattack can negatively impact user and staff safety and well-being, both physical and mental |

In summary, the most common cyber threats to the XR environment reported in the reviewed literature according to the STRIDE model are information disclosure (10/20) followed by tampering (9/20), with most attacks taking place at the client level. Most privacy threats as defined by the developed taxonomies are also information disclosure threats, where user biometric, psychological, and identifying information can be collected through privacy leakage and lead to individual profiling. These threats can impact a health care organization financially and in terms of compliance and community and stakeholder confidence. Most security threats as defined by the taxonomies are tampering threats, the majority of which pose risks to device output integrity and user safety and well-being through immersive manipulation attacks. These threats can impact a health care organization in terms of compliance, service

delivery and capacity, community and stakeholder confidence, finances, and workplace health and safety.

RQ2: How Can Cybersecurity Risks to Clinical XR Systems, In Particular VR Systems, Be Reduced?

Cybersecurity and privacy risks to XR systems were identified in RQ1. RQ2 was answered by mapping the risk mitigation technologies and frameworks against the STRIDE framework to determine which mitigations may mitigate the cyber threats and attacks identified in RQ1, as seen in [Table 8](#). These mitigations were also mapped against the NIST Cybersecurity Framework to identify how and where these mitigations may improve the security posture of a health care organization, as seen in [Table 9](#). NIST is comprised of 5 core functions for organizations to organize their cybersecurity measures: identify, protect, detect, respond, and recover.

Table . Mitigating technologies mapped to STRIDE threat type.

| STRIDE threat | Mitigation | Mitigating technology |
|------------------------|------------------|---|
| Spoofing | Authenticity | <ul style="list-style-type: none"> • Biometric and continuous authentication [38,44] |
| Tampering | Integrity | <ul style="list-style-type: none"> • Trusted execution environments [36] • Virtual reality vulnerability detection and prevention [42] • Adversarial machine learning models to defend against data poisoning [32,36] • Application integrity checks [33] • Static and dynamic analyzers [38] • Intrusion detection systems [45-47,59] • Health care intelligent security model [40] |
| Repudiation | Nonrepudiability | <ul style="list-style-type: none"> • Hardware usage indicators [48] |
| Information disclosure | Confidentiality | <ul style="list-style-type: none"> • Differential privacy [32,36] • Behavioral modifications [36] • Location-based extended reality usage restrictions to dynamically defend against observational privacy leakage [43] • Automated contextual awareness and response [44] • Health care intelligent security model [40] |
| Denial of service | Availability | <ul style="list-style-type: none"> • Design with the principle of redundancy [34] • Intrusion detection systems [45-47,59] • Health care intelligent security model [40] |
| Elevation of privilege | Authorization | <ul style="list-style-type: none"> • Application access control [31,33,43,47-50] • Design with the principle of least privilege [34,51] |

Table . NIST^a cybersecurity framework mapping of mitigations for a health care organization.

| Function | Scope | Mitigating technology or framework |
|----------|--|--|
| Identify | Identify all components in the clinical system. Understand the roles and access levels of everyone that interacts with the system. Identify threats, assets, and risk. Create incident response plans. | <ul style="list-style-type: none"> • ISO 27001/27002/27701 Framework [41] • NIST Privacy Framework [41] • Legislation and regulations [37,41] • Collaboration with users, experts, and developers [37,52] • Privacy policies [35,52] • Threat modeling and risk assessment [34,47,53,54] • Health care data modeling [40] • Penetration testing [42] |
| Protect | Implement defensive technologies that protect system components. Create cybersecurity training and awareness among those that interact with the system. Manage access control and secure data processes. | <ul style="list-style-type: none"> • Differential privacy [32,36] • Behavioral modifications [36] • Trusted execution environments [36] • Application access control [31,33,43,48-50] • Biometric and continuous authentication [38,44] • Virtual reality vulnerability detection and prevention [42] • Design with the principle of least privilege [34,51] • Education and training [31] • Design with the principle of redundancy [34] |
| Detect | Monitor system for unauthorized access and cybersecurity attacks to components. Investigate unusual activity. | <ul style="list-style-type: none"> • Intrusion detection systems [45-47,59] • Static and dynamic analyzers [38] • Application integrity checks [33] • Hardware usage indicators [48] • Health care intelligent security model [40] |
| Respond | Prepare for responding to a cyber incident and minimizing its effect. Respond to cyber incidents through mitigating technologies. Manage communication routes. Plan for notifying stakeholders. Report incident to relevant authorities. | <ul style="list-style-type: none"> • Adversarial machine learning models to defend against data poisoning [32,36] • Location-based extended reality usage restrictions to dynamically defend against observational privacy leakage [43] • Automated contextual awareness and response [44] • Meta crime investigation [35] • Health care intelligent security model [40] |
| Recover | Repair and restore extended reality components and system after a cyber incident. Plan for effective public and stakeholder assurance. Implement lessons learned into framework. Improve organizational resilience. | <ul style="list-style-type: none"> • Code of ethics based on stakeholder perceptions [52] |

^aNIST: National Institute of Standards and Technology.

We found that 18/29 studies (62%) discussed a cyber defence technology or mitigation strategy. These were mapped to a STRIDE category based on the attribute provided by their functionality: authenticity, integrity, nonrepudiability, confidentiality, availability, or authorization. According to the STRIDE framework, threats of a specific STRIDE type may be mitigated by one of the corresponding technologies. For example, designing applications with the principle of least privilege can mitigate elevation of privilege threats such as man-in-the-room attacks [42], to restrict the ability of the attacker to gain access to private VR rooms. Intrusion detection systems can detect anomalous system resource usage indicative of tampering threats like a disorientation attack [33]. Location-based XR usage restrictions can respond to information

disclosure threats, such as by restricting mobile AR usage in a hospital to protect occupant privacy [43].

Cyber defense technologies and mitigation strategies can also be mapped against 3 of these functions: protect, detect, and respond. Papers could identify mitigations of more than one function thus some papers were counted more than once. Some studies explicitly stated the function of their identified technology or strategy, and those that did not were classified based on their stated features. The majority (18 papers) identified a protection function. The next most common defensive technology or strategy was detection (9 papers), followed by response (5 papers). Implementing these technologies and strategies may mitigate risk to a health care

XR system but none of these mitigations have been tested in a clinical context.

In addition to the defensive technologies, management- and operational-level regulations and frameworks will help to identify and mitigate the risks associated with VR/XR systems. One study by King et al [41] identified existing privacy laws, regulations, and frameworks to protect user data privacy in AR. Challenges in these privacy mechanisms include poorly defined data types, inadequate restrictions defined on these data types, improperly defined regulations, and information that should not be collected being undefined. Privacy frameworks to protect consumer information include the ISO 27001/27002/27701 Framework and NIST Privacy Framework. The purpose of the former is to protect personally identifiable information rather than specific information related to health care, while the latter is designed to improve the security and privacy posture of an organization. There are 4 tiers of framework implementation, which delineate to what extent controls are in place to mitigate privacy risks, where the higher the tier, the more controls and protections are in place. Health care organizations often exist at the second tier; by implementing the framework to a higher tier, organizations may be able to enhance data security [41]. These measures fulfill the NIST Framework identify function.

Adams et al [52] developed a VR code of ethics based on the perceptions of users and developers and in collaboration with them, the only instance of the recover function. Only two papers described defensive technologies explicitly applicable to health care services [32,40]. Ara et al [40] proposed a concept for an intelligent security model for a health care organization for detection of and protection against AR-based cybersecurity threats. Physical layer security, secure semantic communication, differential privacy, adversarial machine learning, and privacy bubbles are recommended tools to protect Metaverse-enabled health services [32].

Discussion

Principal Findings

The results of the literature survey indicate that the greatest threats to XR systems in terms of the STRIDE model are information disclosure followed by tampering. These constitute the majority of privacy threats (information disclosure) and security threats (tampering), as defined by the threat taxonomies. Relevant risks of these if VR is used in health care services are confidentiality being breached and user safety and well-being being put at risk. These risks can impact a health care organization in terms of compliance, service delivery and capacity, community and stakeholder confidence, and finances. Identified mitigations were classified using the STRIDE framework, the majority of which provided integrity followed by confidentiality, and potentially addressed the two most common STRIDE threats identified. When mapped against the NIST Cybersecurity Framework, most of these mitigations would fulfill a protective function.

The majority of attacks are an information disclosure threat, and they constitute the majority of privacy threats. These threats are certainly not unique to health care, having been described

in the literature for a variety of XR applications such as in [2,3] and [13], but the consequences for health care can be unique: exposure of patient or staff data; impact on safety and well-being of persons; and legal, financial, and reputational damage. Additionally, it has been shown that VR systems collect a large amount of data from which biometric, psychological, and health-related information can be inferred by an attacker, such as color blindness, mental and physical disability status, physical fitness, and mental acuity [35,36]. This can potentially have severe and unique consequences for a health care VR system. For example, a user undergoing physical rehabilitation can possibly have some data exposed. By the nature of the treatment, they will likely be conducting a range of physical movements that are conducive to inferring certain data types identified by Nair et al [36], such as standing poses to measure anthropometrics and reaction time by measuring the interval between a stimulus and motor response. A malicious actor could tamper with the application to monitor and exfiltrate the data generated during these sessions in a side-channel privacy leakage attack.

Tampering threats are the next most prolific STRIDE threat identified and they constitute the majority of security threats. Guzman et al [3], in their literature review of security and privacy approaches in MR, flag that current systems have poor output access control, contributing to both visual tampering (such as altering renders) and audio tampering (such as altering audio cues or instructions). Most security cyberattacks can be categorized as immersive manipulation, and in a health care setting, these attacks can negatively impact a user's safety, such as by outputting distressing content or causing a user to physically collide with another object by similar tampering. For example, a user in occupational therapy may be exposed to an immersive manipulation physical integrity attack that causes them to collide with an object or health staff in the vicinity. All these cases could negatively impact not only user treatment outcomes, but also their physical and mental health by exacerbating or triggering existing symptoms or creating new health issues altogether. Cybersecurity is a dimension that should be incorporated in risk assessments when considering implementing XR in hospitals, with considerations on the compliance with applicable regulatory measures; the ability and capacity to deliver health services; the confidence of the community and stakeholders in the health care organization; financial performance; and workplace health and safety.

Most of the XR and VR components that were studied for security and privacy issues were HMDs, and the majority of these were the HTC Vive. Thus, current literature focuses heavily on a single type of end-user component and is limited in understanding of security and privacy issues with other components, such as threats to the XR server architecture. The potential risk to other components, including integration with other health care systems, should be investigated for a more holistic understanding of the threat landscape, as retrofitting cybersecurity and privacy controls to deployed systems is challenging [3].

Types of cybersecurity mitigation tools include protective, detective, and responsive strategies and technologies, such as access control and intrusion detection systems. Most of the

mitigations identified in the review provide integrity, potentially reducing the risk of tampering threats. The next most common attribute provided by identified mitigations is confidentiality, which may be effective in mitigating information disclosure threats. These were the two highest risk and most common security and privacy STRIDE threats, respectively. Most of these technologies have not been developed beyond a proof-of-concept and none have been tested in a health care setting. As such, they likely require further investigation into their safety and reliability before they can be used and developed for health care applications. Additionally, the practical challenges and feasibility of implementing them must be understood. The modalities of implementing a mitigation strategy will be highly dependent on the specific health care context and conditions of use of the XR system.

For example, local differential privacy was one proposed mitigation identified in the scoping review that provides confidentiality [32,36]. It protects users from virtual monitoring and identification by adding a degree of error to a user's virtual avatar, so it does not map directly to their physical features. The more error is added, the more likely a user is protected from monitoring, but the more usability is impacted as a user's mental mapping of their physical movements to virtual is changed. This may have side effects or implications for an occupational therapy setting both in terms of effectiveness of treatment and accuracy of data collection and user progress tracking. The degree of error would need to be fine-tuned for the application or treatment, and the usability trade-off [36] may mean in some circumstances this mitigation may not be suitable at all.

The ethical considerations of using XR in health care are not the focus of this paper but must also be addressed before mainstream adoption of this technology into health care. XR has a range of beneficial usages in health care where it has been shown to improve patient outcomes, such as in occupational therapy where VR is effective to engage users. Like most major technology, it is likely that XR and VR will be integrated into the health care industry just as they are being integrated into many other major industries, regardless of their issues in terms of data security and privacy. Adams et al [52] propose a code of ethics for VR developers, encompassing security, privacy, and well-being dimensions and articulating ten principles that show alignment with requirements for quality, safety, and performance in hospitals: (1) do no harm, (2) secure the experience, (3) be transparent about data collection, (4) ask for permission, (5) keep the nausea away, (6) diversity of representation, (7) social spaces, (8) accessibility for all, (9) user centric design and experience, and (10) proactive innovation [52]. In their systematic review of cybersecurity threats of VR and AR, Alismail et al [24] conclude that effective mitigation techniques for VR and AR threats are adopting such a "code of ethics," which is outside of the control of hospitals and users, and these techniques also include adopting a risk assessment approach, as we have articulated above [24].

Another proposed mitigation was biometric-based authentication [38,44], which leverages the data collection capabilities of HMDs to authenticate users based on biometric attributes like movement, providing authenticity, and mitigating some elevation of privilege threats according to the STRIDE

framework. This replaces traditional authentication methods like passwords, which create overhead on the user and rely on them to create and manage the security of passwords. This is inherently insecure. Biometric-based authentication removes this psychological overhead on the user to manage their own security, but for users whose physical mobility may differ from the norm, the effectiveness of this technology may not be the same. Such a mitigation may pose ethical challenges as well as implementation challenges due to potential risk from the exposure of this biometric data. Dick [60] flags that in addition to transparency and disclosure practices, user privacy controls, and information security standards, guidelines and risk assessments should consider the unique risks presented by biometric identifying information.

This risk to data security has been acknowledged and discussed in the literature but the risk to user safety has not. These risks are heightened in a health care setting where attributes can more easily be inferred from VR usage data, and users are potentially more vulnerable. The current health-related data types that can be inferred from VR-generated sensor data like visual acuity, mental capability, and degree of physical fitness are quite general, but cyberattacks may evolve in the future to target more specific health-related attributes and threaten user confidentiality, especially as VR technology is further adopted into health care and gains more public awareness. Immersive manipulation cyberattacks have a similar potential to become more sophisticated and effective in achieving a range of malicious goals, such as undermining treatment outcomes by tampering with clinical VR devices.

These attacks do not rely on any preexisting personal or hospital details stored on the system or even a history of VR usage on the device. These attacks include novel methods unique to XR to gain access to confidential personal, physiological, and health-related attributes about an individual. Regulations, legislations, and policies exist to protect users and professionals from traditional and general risks to privacy and safety—such as the Australian Health Practitioners Regulatory Agency Code of Conduct, which mandates patient safety be made a priority and risk management practices be followed [61], and Health Insurance Portability and Accountability Act legislation in the United States [19]—but these frameworks may not be designed for the novel, unique, and growing threats posed by XR. This may pose legal and ethical dangers for a health care organization, as also mentioned by Morimoto et al [21]. This evolving threat landscape may make the ethical considerations of using XR technology in health care more complex and highlights the fact that the cybersecurity posture in all domains of health care must be proactive rather than reactive to avoid legal, ethical, privacy, and safety problems before they occur.

There has been more primary work done on the security and privacy issues of XR technology in recent years, peaking from 2020 to 2023 as seen in [Multimedia Appendix 3](#). There have also been many literature reviews and secondary analyses similar to this work that were not included in this scoping review. Unlike these existing secondary analyses and as far as the authors are aware, there is little literature focusing on the specific cybersecurity challenges and risks of using XR technology in a health care context or potential countermeasures

against such risks. As such, this scoping review contributed the following: (1) taxonomic analysis and classification of threats and cyberattacks that may be applicable to health care XR applications, (2) STRIDE analysis and classification of threats and countermeasures that may be applicable to health care XR applications, (3) identification of potentially high risk threats to health care XR technologies, (4) ERM mapping of cybersecurity risks and challenges for a health care organization implementing XR, and (5) NIST Cybersecurity Framework mapping of risk mitigations for a health care organization implementing XR.

Limitations

A potential limitation of this scoping review was the variety and quality of results and scholarly sources Google Scholar returned. Any high-quality or important sources in the field not indexed by the search engine were omitted. This aspect of the study could possibly be strengthened in future work by searching from a range of other scholarly sources.

Conclusion

The most significant threats posited for a health care VR system in terms of the STRIDE framework were information disclosure followed by tampering threats. VR systems generate a large amount of data from the sensors on board, data which may be used to infer additional attributes about users including personal and health-related attributes, such as physical fitness. This poses real risks in clinical environments, as privacy attacks may lead to breaches of user confidentiality. Immersive manipulation attacks constitute the majority of security threats. If a clinical VR device is compromised by a cyberattacker, they can tamper with the delivery and content of a clinical VR immersive session, which may affect the delivery of care and potentially the safety

and well-being of individuals. These risks have implications on regulatory compliance, health service delivery, communities, staff health and safety, and the financial performance of a health care organization. The majority of mitigations identified for these threats address information disclosure and tampering and provide protective capabilities for an organization according to the NIST Cybersecurity Framework. However, only 3 of 29 included papers mentioned health care and none of the threats and mitigations identified have been studied in or assessed for health care. This can present ethical and practical implementation challenges for a health care organization. The specific cybersecurity and privacy risks presented by XR technology should be considered as a part of system-wide digital risk management frameworks by health organizations, within their proposed context of use, intended purpose, and perceived benefits to health care delivery and individuals.

Future Directions

The specific cybersecurity and privacy risks related to XR technology used in health care services require dedicated studies. Due to the wide range of clinical applications of this technology, the risks for each health service should be studied individually. Only threats to end-user devices were investigated. Considering XR systems usually involve more than one component, future work can also study the threats to other XR components such as the controllers and servers. Mitigation strategies and technologies currently suggested by the literature must be assessed for their practical feasibility and effectiveness for health care applications. The effectiveness of existing regulations, frameworks, and policies in health care for assessing and mitigating the unique risks posed by XR technology to user privacy and well-being also requires investigation.

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Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during this study.

Authors' Contributions

The authors contributed the following to this work according to the CRediT taxonomy. KL was involved in the conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing (original draft), writing (review and editing), and visualization. AMK was involved in the conceptualization, methodology, investigation, writing (review and editing), supervision, project administration, and funding acquisition. MD was involved in the conceptualization, methodology, investigation, writing (original draft), writing (review and editing), and funding acquisition. APLB was involved in the conceptualization, writing (review and editing), supervision, and funding acquisition. RAMA was involved in the conceptualization and writing (review and editing). JF was involved in the conceptualization, writing (review and editing), and funding acquisition. NB was involved in the conceptualization, writing (review and editing), supervision, project administration, and funding acquisition. DDK was involved in the conceptualization, methodology, writing (review and editing), visualization, supervision, and funding acquisition.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Electronic database search strategy.

[\[DOC File, 55 KB - xr_v1i1e59409_app1.doc \]](#)

Multimedia Appendix 2

Summary of papers.

[\[DOC File, 85 KB - xr_v1i1e59409_app2.doc \]](#)

Multimedia Appendix 3

Studies published per year.

[\[PNG File, 7 KB - xr_v1i1e59409_app3.png \]](#)

Multimedia Appendix 4

Glossary.

[\[DOC File, 43 KB - xr_v1i1e59409_app4.doc \]](#)

Multimedia Appendix 5

Cyber attack catalogue.

[\[DOC File, 54 KB - xr_v1i1e59409_app5.doc \]](#)

Multimedia Appendix 6

Privilege level summary.

[\[DOC File, 49 KB - xr_v1i1e59409_app6.doc \]](#)

Checklist 1

PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) checklist.

[\[PDF File, 556 KB - xr_v1i1e59409_app7.pdf \]](#)**References**

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Abbreviations

AI: artificial intelligence

AR: augmented reality

DoS: denial of service

ERM: enterprise risk management

HMD: head-mounted display

ML: machine learning

MR: mixed reality

NIST: National Institute of Standards and Technology

PRISMA-ScR: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews

STRIDE: spoofing, tampering, repudiation, information disclosure, denial of service, and elevation of privilege

VR: virtual reality

XR: extended reality

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Enhancing Executive Function Skills in Children With Attention-Deficit/Hyperactivity Disorder via Immersive Virtual Reality Interventions: Scoping Review

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Abstract

Background: This scoping review investigated immersive virtual reality (IVR) interventions for improving executive function skills of children and adolescents with attention-deficit/hyperactivity disorder (ADHD).

Objective: This study aimed to identify and closely inspect the characteristics of these interventions and provide a summary of key findings to guide researchers in their future investigations.

Methods: A search across Web of Science, Scopus, PubMed, and APA PsycInfo databases was carried out with restrictions of publication date (2000 - 2023) and language (English). The inclusion criteria were (1) research articles, excluding protocols, book chapters, reviews, and meta-analyses; (2) usage of IVR, excluding computer-based VR or augmented reality technologies; (3) aim of targeting executive function skills; (4) sample of children and adolescents diagnosed with ADHD (with or without learning disorder comorbidity); and (5) intervention studies (quasi-experimental clinical trials and randomized controlled trials, excluding assessments). Finally, the characteristics of the studies were summarized and inspected.

Results: The search yielded 2484 potential records. After a rigorous screening process, 6 articles (5 randomized controlled trials and 1 pilot study) were included. A certain heterogeneity in duration, designs of IVR interventions, and outcome measures were observed. All studies reported overall improvements in the attentional performances of children; however, only a few reported improvements in executive functions. In addition, a tendency toward integration of neurofeedback systems with IVR technologies was observed.

Conclusions: Because of the specific objectives and related inclusion and exclusion criteria of this review, only a few interventions could be included and analyzed. Even though there seem to be promising applications of IVR for children and adolescents with ADHD, heterogeneity in intervention characteristics accompanied by observed overall high or serious risk of bias prevented the authors from making generalized conclusions.

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KEYWORDS

immersive virtual reality; ADHD; neurofeedback; executive functions; systematic review; adolescent; attention-deficit/hyperactivity disorder; behavioral therapy; digital health tools; neurodiversity; virtual reality; digital mental health

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common neurodevelopmental disorders in children and adolescents. Commonly diagnosed during childhood, the disorders often persist into adulthood [1]. Generally characterized by levels of inattention, impulsivity, and hyperactivity, ADHD leads to impairment in daily life [2]. To date, interventions for ADHD have included medication therapy,

behavioral therapy (cognitive behavioral therapy [CBT]), or a combination of both [3]. While a patient undergoing CBT receives sessions involving cognitive and behavioral training, classical psychopharmacological treatment includes the prescription of methylphenidate dextroamphetamine or pemoline [4]. While these approaches proved effective for rehabilitation, they come with several drawbacks, such as time consumption, and in some cases, a lack of behavioral improvement [5,6]. Consequently, alternative options, particularly the use of technological tools, have been explored.

Recent technological advancements have led to the integration of interventions with the use of digital health tools. Digital health tools refer to the use of any kind of technology for the purpose of delivering health assessments and interventions. Such tools are in a wide range: from emails sent by doctors for informing patients to the use of virtual reality (VR) for treatment purposes [7,8]. For ADHD treatment, VR technologies have become one of the trending digital health tools [9,10].

VR can be defined as a sensory illusion achieved through computer technology consisting of hardware and software that simulates in real-time (physical) presence of users and their interaction in an environment that is virtually created. This definition is consistent with the literature [11] and independent of technology. Moreover, VR is considered a recent technology that started 50 years ago, and for more than 2 decades now, researchers and clinicians have been working with VR to build tools to enhance clinical research, assessment, and intervention [12]. The benefits of using this technology include increased immersion, feeling of presence, and motivation for patients during the treatment process which is determinant in the science of rehabilitation [12-15].

VR systems have been usually classified as either immersive or nonimmersive systems [16], and qualified as low- or high-immersive VR [17]. Low-immersive (or nonimmersive) VR refers to technological devices such as desktop computer screens, whereas high-immersive VR is primarily linked to head-mounted display (HMD) systems and Cave Automatic Virtual Environment systems [18]. There are criticisms about “desktop VR” in the literature because it does not allow the user to interact naturally in the virtual environment and fails to induce an immersive experience [14,16,18]. This is why, in this review, we focus on research settings where children can fully experience immersive virtual environments, therefore only including studies using immersive virtual reality (IVR).

The objective of this review is (1) to identify published IVR interventions that target executive function skills of children diagnosed with ADHD, (2) to closely inspect the characteristics of these interventions through descriptive or narrative analysis, and (3) to provide a summary of key findings to guide researchers in their future investigations.

Methods

Search Strategy

The articles included in this research have been collected from the search databases Web of Science, Scopus, PubMed, and

APA PsycInfo. The initial search was carried out on October 11, 2022, with restrictions of publication date 2000 - 2023 and English language by 2 independent reviewers (MB and NF) and lastly updated on December 29, 2023. The PICO (Patient, Population or Problem, Intervention, Comparison, and Outcome) model [19] was followed while deciding on the search terms (see [Multimedia Appendix 1](#)). The comparison and outcome part of the PICO model (see [Multimedia Appendix 1](#)) was not included among the search terms as it could restrict the search results [20].

All databases were searched with identical search terms. See [Multimedia Appendix 2](#) for a detailed list of search terms for each database.

Selection of Studies and Data Collection Process

After searching the databases, the data were extracted in Microsoft Excel format with the following information about the articles: DOI number, title of the articles, abstracts, authors, publication year, and name of the source title (search database). After exporting data from each database, it was combined into a single file and duplicates were subsequently eliminated. Two independent titles and abstract screening were carried out according to this information. Lastly, the full text of each article was examined by the 3 reviewers (AK, MB, and NF). Any disagreement between them over the eligibility of any study was resolved with an examination of the fourth reviewer (PB-K). The resulting studies were included in the final data according to the following criteria. (1) Only research articles were included; protocols, book chapters, reviews, and meta-analyses were excluded. (2) Only IVR techniques were included. (3) The target of the studies should be patients with ADHD, learning disorders, or both as comorbid diagnoses. (4) Only studies targeting children and adolescents were included. (5) Only intervention studies (quasi-experimental clinical trials and randomized controlled trials [RCTs]) were included.

A descriptive or narrative data analysis method was followed. The following information about the articles was extracted: country of the research, participant characteristics (sample size, diagnosis, and age), measures that are used in pre- and postassessments, and outcomes. A summary of this information is presented in [Table 1](#).

Table . Summary of the characteristics of papers included in the review.

| Reference | Study characteristics | Participant characteristics | Intervention groups | Measures (pre- and postassessment) | Outcome and results |
|--------------------|---|--|---|--|---|
| Cho et al [21] | <ul style="list-style-type: none"> Country: Korea Design: RCT^a | <ul style="list-style-type: none"> Number of participants: 50 Diagnosed with ADHD^b: no Comorbidity: no Age: 14 - 18 years | <ol style="list-style-type: none"> No intervention (control group) Desktop VR^c electroencephalography biofeedback training Desktop VR cognitive training VR electroencephalography biofeedback training VR cognitive training | <ul style="list-style-type: none"> For ADHD symptoms: CPT^d | <ul style="list-style-type: none"> For ADHD symptoms: significant improvement for experimental groups ($P < .01$) |
| Cho et al [22] | <ul style="list-style-type: none"> Country: Korea Design: RCT | <ul style="list-style-type: none"> Number of participants: 28 Diagnosed with ADHD: no Comorbidity: no Age: 14 - 18 years | <ol style="list-style-type: none"> No intervention (control group) Non-VR group VR group | <ul style="list-style-type: none"> For ADHD symptoms: CPT | <ul style="list-style-type: none"> For ADHD symptoms: statistically significant improvement in attention enhancement for the VR group ($P < .01$) |
| Bioulac et al [23] | <ul style="list-style-type: none"> Country: France Design: RCT | <ul style="list-style-type: none"> Number of participants: 51 Diagnosed with ADHD: yes Comorbidity: no Age: 14 - 18 years | <ol style="list-style-type: none"> Placebo psychotherapy group Methylphenidate group Therapy by virtual remediation or VR group | <ul style="list-style-type: none"> For attention: a virtual classroom task For ADHD symptoms: ADHD-RS^e and CPT II | <ul style="list-style-type: none"> For attention: significantly higher scores for the VR group compared to the psychotherapy group ($P < .0001$) and the methylphenidate group ($P < .0001$) |
| Ou et al [24] | <ul style="list-style-type: none"> Country: Taiwan Design: Pilot | <ul style="list-style-type: none"> Number of participants: 3 Diagnosed with ADHD: yes Comorbidity: no Age: 8 - 12 years | <p>Three different immersive virtual reality games with HTC VIVE (HTC Corp) focusing on hand-eye and hand-foot coordination:</p> <ol style="list-style-type: none"> Fishing Master Fruit Train Ocean Manager | <ul style="list-style-type: none"> For nonverbal intelligence: TONI-4^f For executive functions: WCST^g For attention: ATESC^h For ADHD and oppositional defiant disorder symptoms: SNAP-IVⁱ | <ul style="list-style-type: none"> For nonverbal intelligence: overall improvement For executive functions: overall improvement For attention: overall improvement For ADHD and oppositional defiant disorder symptoms: overall improvement |
| Skalski et al [25] | <ul style="list-style-type: none"> Country: Poland Design: RCT | <ul style="list-style-type: none"> Number of participants: 87 Diagnosed with ADHD: yes Comorbidity: no Age: 9 - 15 years | <ol style="list-style-type: none"> Standard HEG BFB^j group (desktop) VR HEG BFB^k with distractors (2D) VR HEG BFB without distractors (3D) | <p>For attention:</p> <ul style="list-style-type: none"> The visual search task The multitasking test The short form of Mackworth Clock Task | <ul style="list-style-type: none"> For attention: better performance of children in VR HEG BFB groups ($P < .0001$) |

| Reference | Study characteristics | Participant characteristics | Intervention groups | Measures (pre- and postassessment) | Outcome and results |
|-------------------|---|---|--|---|--|
| Schena et al [26] | <ul style="list-style-type: none"> Country: Italy Design: RCT | <ul style="list-style-type: none"> Number of participants: 60 Diagnosed with ADHD: yes Comorbidity: learning disorder Age: 5 - 12 years | <ol style="list-style-type: none"> Traditional (conventional) therapy VR therapy with the IAmHero system | <ul style="list-style-type: none"> For attention and concentration skills: BIA^l For ADHD symptoms and behavioral disorders: Conners-3 questionnaire For executive functions: TOL^m | <ul style="list-style-type: none"> For attention and concentration skills: improvement in areas of attentional processes and sustained auditory attention ($P<.05$) For ADHD symptoms and behavioral disorders: improvement especially for hyperactivity or impulsivity subtype ($P<.05$) For executive functions: improvement in task planning and organization ($P<.05$) |

^aRCT: randomized controlled trial.

^bADHD: attention-deficit/hyperactivity disorder.

^cVR: virtual reality.

^dCPT: continuous performance test.

^eADHD-RS: attention-deficit/hyperactivity disorder rating scale.

^fTONI-4: Test of Nonverbal Intelligence, Fourth Edition.

^gWCST: Wisconsin Card Sorting Test.

^hATESC: attention test for elementary school children.

ⁱSNAP-IV: Swanson, Nolan, and Pelham Questionnaire Version 4.

^jHEG BFB: hemoencephalographic biofeedback.

^kVR HEG BFB: hemoencephalographic biofeedback with virtual reality.

^lBIA: Italian Battery of ADHD.

^mTOL: Tower of London test.

The common and different points of the articles on their outcomes, assessments, and intervention characteristics are explained and summarized in the Results section.

Results

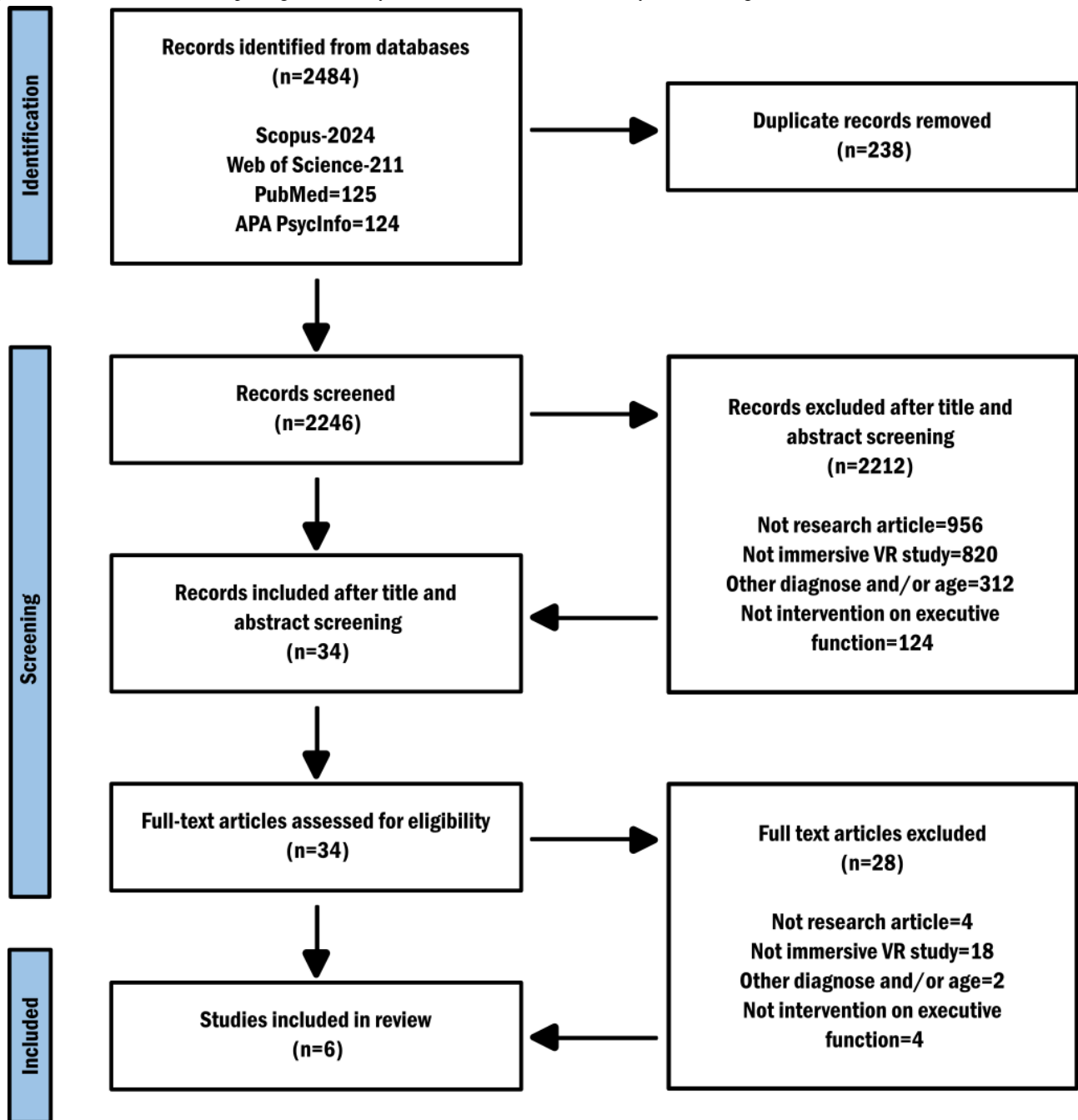
Study Selection and Characteristics

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram is shown in [Figure 1](#). Initially, 2484 articles were identified through 4 databases; after removing the duplicates, the remaining 2246 were screened based on the titles and abstracts. The results of this screening process were the identification of 34 studies, and the exclusion

of 2212 studies, based on the inclusion and exclusion criteria. Three independent reviewers (AK, MB, and NF) assessed the methodological quality of the studies included. In the first screening phase, the criteria that led to the greatest exclusion of articles were criterion 1 (not research article) and criterion 2 (not immersive VR study). Precisely 956 articles were excluded for criterion 1, and 820 for criterion 2.

Later, the 34 identified articles were downloaded for a full-text screening. Of these, 28 were excluded for various reasons: being book chapter or protocol (4), using non-immersive technologies (18), study samples within other diagnoses and age groups (2), not being intervention but assessment on executive functions (4). Finally, 6 articles were included in the review.

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



Evaluation Outcomes

Origin of Studies

The selected articles originate from Asia (3 articles) and Europe (3 articles). There are no articles from the United States.

Study Design

The review included 5 RCTs [21-23,25,26] and 1 pilot study [24]. The pilot study was included in the review because of its design characteristics, which is explained below. Except for the pilot study, all 5 studies included control and comparison groups in their experimental designs.

Participant Characteristics

Among the studies, there were variations in the ages of the participants. Cho et al [21] included 50 and Cho et al [22] included 28 children with the oldest age range (14-18 years), while Bioulac et al [23] included 51 children aged between 7 and 11 years, and Schena et al [26] included 60 children aged between 5 and 12 years. The pilot study of Ou et al [24] included 3 children in their sample who were aged between 8 and 12 years. Skalski et al [25] included 90 children, the widest participant's age range (9-15 years).

For diagnoses of children, Ou et al [24] did not provide clear information about the diagnoses of children, as they stated "had some difficulty in learning in school, and they were inattentive, impulsive, hyperactive, and distracted. Although they were not officially diagnosed as ADHD, about 30% of them most likely

had ADHD.” Cho et al [21,22] also mentioned their participants as “not officially having diagnoses of ADHD, but they had some difficulty in learning and were inattentive, impulsive, hyperactive and distracted.” The remaining 3 studies stated children’s diagnoses as ADHD. Among 6 articles, only Schena et al [26] did not exclude comorbidity of learning disorders in their sample.

Characteristics of VR Interventions

Overview

Although there are variations in VR technology, primarily resulting from the 20-year gap between the oldest and most recent publications, all the studies included in this review used immersive VR interventions. Thus, they provide an interactive and engaging environment for the assessment or treatment of ADHD symptoms and executive dysfunctions in children. However, there are variations in intervention designs and duration across the publications.

Design of Interventions

Cho et al [21] presented an electroencephalography biofeedback system combined with IVR specifically designed for treating ADHD in a virtual classroom, which is called virtual reality cognitive training; the authors compare this training between groups either with VR, or only with a computer screen and no intervention group. Cho et al [22] compared HMD usage for neurofeedback training in a virtual classroom with its only computer screen usage. Skalski et al [25] used hemoencephalography biofeedback and compared its use in IVR, desktop VR, and the standard version (2D game presented on a 21-inch television screen). Bioulac et al [23] compared virtual remediation with methylphenidate, as the only study in this review that compared the effectiveness of medical intervention with an IVR design.

Two studies [24,26] designed and conducted game-like interventions within IVR. Ou et al [24] focused on VR rehabilitation games for ADHD symptoms and developed three different games for their pilot study: (1) Fishing Master, for improving hand-eye coordination; (2) Fruit Train, for improving physical coordination of upper and lower limbs; and (3) Ocean Manager, for improving visuomotor skills. They tested these games without involving comparison/control groups. Schena et al [26] used the IAMHero tool, which targets ADHD symptoms and executive dysfunctions. It consists of three games: (1) Topological Categories, for improving visual-spatial orientation, motor coordination, planning, and selective auditory attention; (2) Infinite Runner, for improving visuomotor skills; and (3) Space Coding, for improving motor skills, planning, visuospatial and constructive skills, reasoning, and problem-solving.

Duration of Interventions

The duration of the interventions lasted from 1.5 to 6 months, with the frequency ranging between 1 and 3 times per week. In the studies of Cho et al [21,22], subjects in both experimental and placebo groups underwent 8 sessions over 2 weeks, each session lasting for 20 minutes. The control group did not receive any training sessions in the meantime. These sessions were conducted twice a week for 6 weeks. In the study of Ou et al

[24], the participants went through 36 sessions. These sessions were conducted 3 times a week for 3 weeks within a 3-week cycle for each game. Each session was divided into three 10-minute segments. In the study of Skalski et al [25], the experimental group underwent 10 sessions. These sessions were conducted once a week, and each session was divided into three 10-minute segments. In the study of Schena et al [26], the trials lasted for 6 months; the experimental group received weekly 30 minutes of IVR intervention within each 50 minutes (the remaining 20 minutes were designed as free play in the therapy room) as an addition to their ongoing therapy sessions from the center that they receive treatment. The control group received weekly sessions (2 per week) of speech and psychomotor treatment, which are designed based on the patient’s clinical needs.

Assessments and Outcomes

Assessments

The authors observed heterogeneity in the selection of assessments and outcome variables.

Cho et al [21] conducted continuous performance test (CPT) assessments before and after the training sessions to measure attention and impulsivity in all the participants. CPT scores were analyzed and compared between the 3 groups: experimental group 1 (VR), experimental group 2 (non-VR group), and no-intervention control group. Cho et al [22] conducted CPT assessments before and after the training sessions to measure attention and impulsivity in all the participants. CPT scores were analyzed and compared between the 5 groups: experimental group 1 (virtual reality electroencephalography biofeedback training), experimental group 2 (VR cognitive training), placebo group 1 (desktop VR electroencephalography biofeedback training), placebo group 2 (desktop VR cognitive training), and control group (no intervention).

Bioulac et al [23] conducted pre- and postassessments for participants’ performance in (1) attention with the visual classroom task and (2) ADHD symptoms with the ADHD rating scale (ADHD-RS) and continuous performance test II (CPT II).

The pilot study of Ou et al [24] was conducted before and after assessments for participants’ ADHD symptoms with CPT II for each experimental session. The authors considered several variables, such as response time, SD of the response time (as a measure of variability or consistency), variability, errors of commission (as a measure of impulsivity or failure to inhabit response), errors of omission (as a measure of inattention), and response sensitivity (as a measure of diminishing performance over time).

In the study of Skalski et al [25], the participants were assessed for their intelligence at the recruitment stage with Raven’s colored progressive matrices in Polish standardization. For the interventions, the participants were assessed for their selected aspects of attention with (1) the short form of the Mackworth Clock Task for vigilance, (2) the visual search task for attention in the conjunctive search paradigm, and (3) the multitasking test for divided attention (see [Multimedia Appendix 3](#) for details of assessment procedures).

In the study of Schena et al [26], participants were assessed for their cognitive profile in the recruitment stage with the Wechsler Intelligence Scale for Children, 4th edition. In the pre- and postintervention phases, participants were assessed with the Italian Battery of ADHD for their attention and concentration skills, with the Conners-3 questionnaire for the assessment of ADHD and behavioral disorders, and finally with the Tower of London test for assessing their strategic decision-making and problem-solving skills.

Outcomes

All the studies reported improvements in the attentional performances of children by looking at differences between the pre- and postassessments. The pilot study of Ou et al [24] provided only a comparison between numerical values without any statistical analyses. The studies of Cho et al [21,22], Bioulac et al [23], Skalski et al [25], and Schena et al [26] presented their results with statistically significant results.

The analysis of Cho et al [21] showed that there were significant improvements for experimental groups in the number of correct answers, omission errors, and response sensitivity ($P < .01$). The control group indicated no significant change. There was a reduction in commission errors and response times for experimental groups too, but those results were not statistically significant.

The analysis of Cho et al [22] showed that the main effect for the measurement time ($F_{1,25}=39.775$, $P < .01$) and the interaction effect of group \times the measurement time ($F_{2,25}=8.715$, $P < .01$) were significant, thus the number of hits in CPT II of the VR group increased compared to the non-VR and control groups. Regarding the reaction time in CPT II, the analysis showed a significant main effect for the measurement time ($F_{1,25}=8.545$, $P < .01$) indicating a decrease in the reaction time of the VR group after training, implying that participants paid more attention to the tasks. Additionally, for the omission error in CPT, the main effect for measurement time ($F_{1,25}=31.179$, $P < .01$) and the interaction effect of a group \times the measurement time ($F_{2,25}=7.273$, $P < .01$) were significant. Omission errors for the VR group decreased further than for non-VR and control groups. After training, both groups showed fewer commission errors. The main effect of the measurement time on commission errors ($F_{1,25}=5.698$, $P < .05$) and response bias ($F_{1,25}=7.724$, $P < .01$) were significant.

The analysis of Bioulac et al [23] showed that for virtual classroom task, there were significant differences in the number of correct hits for all the groups ($F_{2,47}=14.56$, $P < .0001$) and for the number of commissions ($F_{2,47}=3.01$, $P = .05$). The number of correct hits for the VR group was significantly higher than the psychotherapy group ($P < .0001$) and the methylphenidate group ($P < .0001$). For the number of commissions, the VR group was significantly lower than the methylphenidate group ($P < .0001$), while it was equivalent to methylphenidate and psychotherapy groups. For ADHD-RS, there were significant differences between the groups on ADHD-RS total ($F_{2,45}=20.98$, $P < .0001$).

The pilot study of Ou et al [24] reported an overall improvement in nonverbal intelligence, executive functions, attention and symptoms of ADHD, and oppositional defiant disorder.

The analyses of Skalski et al [25] showed that children who participated in hemoencephalographic biofeedback with virtual reality (VR HEG BFB) with distractors (2D) and VR HEG BFB without distractors (3D) performed significantly better than children who participated in the standard HEG BFB (desktop) group with regard to all dependent variables of the measurement: omission errors (Group A: $P = .018$; Group B: $P = .002$), commission errors (Group A: $P = .007$; Group B: $P = .003$), response time slope in visual search (Group A: $P = .007$; Group B: $P < .001$), single tasks (Group A: $P = .011$; Group B: $P = .006$), as well as multitasks (Group A: $P = .021$; Group B: $P < .001$).

The analyses of Schena et al [26] showed that there is a significant improvement in participants' mean scores between pre-test (t_0) and post-test (t_1) assessments in areas of attentional processes, problem-solving (mean _{t_0} 94, SD 12.76; mean _{t_1} 97.52, SD 5.47; $P < .05$) sustained auditory attention (mean _{t_0} 7.21, SD 0.65; mean _{t_1} 9, SD 0.36; $P < .05$) and executive functions (ie, task planning and organization; mean _{t_0} 24.45, SD 5.65; mean _{t_1} 27.79, SD 3.66, $P < .05$).

Discussion

Principal Results

The main goal of this scoping review was (1) to identify published IVR interventions that target executive function skills of children diagnosed with ADHD, (2) to closely inspect the characteristics of these interventions through descriptive or narrative analysis, and (3) to provide a summary of key finding and produce recommendations to guide researchers for their future investigations. Identify and analyze the characteristics of IVR interventions for improving executive function skills of children with ADHD.

The first point catching attention is the very limited number of publications that met the selection criteria. Indeed, our results show that among more than 2000 articles published in the last 22 years, only 6 studies meet our inclusion criteria. These criteria encompass research articles from 2000 to 2023 considering IVR interventions for children diagnosed with ADHD, learning disorders, or both as comorbid conditions. When looking more in detail, the 2 criteria which eliminated the greatest number of publications are "not research article," with 956 articles discarded, and "not immersive VR" with 820 articles discarded. This shows that almost half of the articles we found were not research articles. That is to say that during the last 22 years, a large part of the published articles concerning ADHD were not experimental studies but generic articles, protocols, book chapters, reviews, and meta-analyses. This is intriguing, as it suggests that despite ADHD being a significant and actively researched subject, nearly half of the scientific literature on this topic does not directly report experiments, or only partially. This might indicate that experimental studies on ADHD present considerable challenges or at least that experimentally studying ADHD is more difficult than it seems especially when using IVR.

The second most discriminating exclusion criterion, the use of IVR, can probably be explained by the fact that initially IVR was not easily accessible and reserved for laboratories with large financial resources or specialized in IVR. Hence, the preference is for a less immersive setup that is more technologically and economically accessible. One can guess that with the democratization of IVR, there will be an augmentation of the IVR experimental setup. Indeed, with the falling cost of VR technologies and the development of high-quality HMDs, the use of IVR in learning environments may become more widespread in the future [27-29].

On the other hand, our findings revealed heterogeneity in the study designs (5 RCTs and 1 pilot study). Furthermore, there were variations in the outcome measures, except for the Continuous Performance Test (editions I and II), which was commonly preferred by Cho et al [21,22] and Bioulac et al [23]. All studies involved children and adolescents diagnosed with ADHD or exhibiting possible symptoms observed by the researchers. The authors included learning disorder in the database searches, considering the high comorbidity rate between ADHD and learning disorder. However, only 1 of the 6 studies [26] included participants diagnosed with learning disorder as comorbid. Regarding VR interventions, there was a tendency to combine biofeedback (ie, neurofeedback) systems with IVR technologies.

As highlighted by this scoping review, the use of biofeedback (ie, neurofeedback) systems appears to be a trending digital health tool for the treatment of developmental disorders, particularly ADHD [30-32]. The objective of these interventions was to train and reinforce patients for desired cortical activities, which were observed with electroencephalography signals. Indeed, cortical activities of patients with ADHD were found to differ in comparison with healthy individuals for the desired tasks [31,32]. The interest of researchers in using biofeedback systems for ADHD stems from “side effects and inadequate response to current medical treatments” [31], but also because certain patients with ADHD did not benefit from CBT interventions [32]. With the application through integrations of biofeedback with VR systems, we can expect to see more interventions in the future that combine biofeedback with IVR.

Comparison With Prior Work

Previous reviews with similar objectives also found a small sample size. For instance, a recent study [9] aimed to evaluate the effectiveness of VR-based interventions (without specifying a target cognitive skill) for children with ADHD and could only include 6 studies for its qualitative analysis and 4 for quantitative analysis. Another study published the same year as [33] and looking at VR interventions with children (without specifying any mental health disorder) only included 19 studies. These findings, combined with our results, highlight the scarcity of RCTs investigating the use of IVR specifically for children.

Furthermore, the literature highlighted some aspects that indicate the potential benefits of this technology for children. First, IVR could significantly increase the ecological validity and reliability of behavioral interventions. In other words, the abilities that

were gained by interventions might be more easily transformed to the daily settings of children, since the tool itself gave the opportunity to create environments that are similar to real-world environments [34].

Second, children might become more motivated to the rehabilitation process by the use of up-to-date technologies (ie, VR) since it can make the process more enjoyable for them. Previous work in the literature indicated that treatments that were more enjoyable for children and adults could lead the treatment process to be easier, healthier, and more effective [14,35,36]. As mentioned before, this review included interventions providing interactive and engaging environments for children, which refers to “game-like” applications.

In further research with IVR, game design elements can be provided with a greater sense of interactivity owing to its immersive experience, which can increase user engagement and benefits of interventions [32].

Limitations

This scoping review has certain limitations. First, due to the specific objectives and related inclusion and exclusion criteria of the study, only a few interventions could be included and analyzed.

Another limitation of this study is the use of the PICO framework while deciding on search terms. However, built-in features of databases such as MeSH (Medical Subject Heading) terms were not used, which could limit the results.

Conclusions

Our study showed that only 6 studies were in line with our inclusion criteria. A certain heterogeneity in the study designs and outcome measures was observed.

All the studies included participants with diagnoses (or possible symptoms observed by researchers) of ADHD and only 1 of the 6 studies included participants with learning disorders as comorbidity. The age range of the participants varied between the studies.

For IVR interventions, a tendency to combine biofeedback systems with immersive reality technologies was observed. However, this observation cannot be generalized due to the limited sample size. To test the advantages of IVR and the effectiveness of the interventions with systematic reviews and meta-analyses, more research should be conducted. As Ou et al [24] suggested, further research should also investigate suitable designs for different age and gender groups.

About 60 years ago, Ivan Sutherland developed the first HMD system called the “Sword of Damocles” [37]. However, it was only about 15 years ago that significant advancements were made in both hardware and software, permitting the rise of consumer VR headsets and the democratization of IVR. Hence, it seems clear that IVR is a promising technology with encouraging results and great potential for many applications. However, it also seems clear that this is a relatively young technology that requires more comprehensive and more in-depth studies, in particular.

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Disclaimer

The authors state that no generative artificial intelligence tool was used in any portion of the manuscript.

Authors' Contributions

PB-K and AK designed and planned the study. MB and NF contributed to the development of the research questions and methodology, and conducted data collection, data processing, and contributed to data analysis in collaboration with AK. PB-K, AK, MB, and NF were involved in writing the initial draft of the manuscript. PB-K and AK contributed to data interpretation, and critically reviewed, edited, and approved the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

PICO (Patient problem, Intervention, Comparison, and Outcome) model.

[\[DOCX File, 17 KB - xr_v1i1e57225_app1.docx\]](#)

Multimedia Appendix 2

Search strategies.

[\[DOCX File, 18 KB - xr_v1i1e57225_app2.docx\]](#)

Multimedia Appendix 3

Assessment procedures.

[\[DOCX File, 16 KB - xr_v1i1e57225_app3.docx\]](#)

Checklist 1

PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) checklist.

[\[PDF File, 316 KB - xr_v1i1e57225_app4.pdf\]](#)

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Abbreviations

- ADHD:** attention-deficit/hyperactivity disorder
ADHD-RS: attention-deficit/hyperactivity disorder rating scale
CBT: cognitive behavioral therapy
CPT: continuous performance test
CPT II: continuous performance test II
HMD: head-mounted display
IVR: immersive virtual reality
MeSH: Medical Subject Heading
PICO: Patient problem, Intervention, Comparison, and Outcome
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT: randomized controlled trial
VR: virtual reality
VR HEG BFB: hemoencephalographic biofeedback with virtual reality

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Review

Barriers and Facilitators to the Implementation of Virtual Reality Interventions for People With Chronic Pain: Scoping Review

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Abstract

Background: Chronic pain is a growing health problem worldwide with a significant impact on individuals and societies. In regard to treatment, there is a gap between guideline recommendations and common practice in health care, especially concerning cognitive and psychological interventions. Virtual reality (VR) may provide a way to improve this situation. A growing body of evidence indicates that VR therapy has positive effects on pain and physical function. However, there is limited knowledge about barriers and facilitators to the implementation of VR interventions for people with chronic pain in health care settings.

Objective: The aim of this study was to identify and analyze the barriers and facilitators involved in implementing VR interventions for people with chronic pain.

Methods: We conducted a scoping review of the German and English literature using the MEDLINE, Cochrane Central Register of Controlled Trials, CINAHL, PEDro, LILACS, and Web of Science (inception to November 2023) databases, including quantitative, qualitative, and mixed methods studies reporting barriers and facilitators to the implementation of VR interventions for people with chronic pain, as reported by patients or health care professionals. Two reviewers systematically screened the abstracts and full texts of retrieved articles according to the inclusion criteria. All mentioned barriers and facilitators were extracted and categorized according to the Theoretical Domains Framework (TDF).

Results: The database search resulted in 1864 records after removal of duplicates. From the 14 included studies, 30 barriers and 33 facilitators from the patient perspective and 2 facilitators from the health care professional perspective were extracted. Barriers reported by people with chronic pain were most frequently assigned to the TDF domains environmental context (60%) and skills (16.7%). Most facilitators were found in three domains for both the patients and health care professionals: beliefs about consequences (30.3%), emotions (18.2%), and environmental context (18.2%).

Conclusions: The findings of this review can inform the development of strategies for future implementations of VR interventions for people with chronic pain. Additionally, further research should address knowledge gaps about the perspective of health care professionals regarding the implementation of VR interventions for people with chronic pain.

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KEYWORDS

virtual reality; VR; chronic pain; implementation science; scoping review; barriers; facilitators

Introduction

Chronic pain is defined as persistent or recurrent pain lasting longer than 3 months [1]. Chronic pain is an increasingly prevalent health condition worldwide, as three of the primary

contributors to years lost to disability in recent decades are chronic pain conditions (back pain, musculoskeletal disorders, and neck pain) [2,3]. Estimated pooled prevalence rates for chronic pain in adults vary across studies from 20.5% in the United States [4] to 28.3% in Germany [5], 34% in the United

Kingdom [6], and 48.1% in Chile [7]. High prevalence of chronic pain is not only found in industrial nations but also in low- and middle-income countries, where the prevalence ranges from 13% to 49.4% [8]. Chronic pain affects not only adults but also has a significant prevalence in children, adolescents, and young adults, ranging from 8% to 23% [8-10]. Common consequences of chronic pain include physical disability, psychological distress, and reduced quality of life [3,11]. Furthermore, chronic pain affects relationships and self-esteem and is associated with higher rates of divorce and suicide [12,13]. From a societal perspective, chronic pain places an enormous financial burden on health care systems. In Australia, the financial costs associated with chronic pain were estimated to be ~US \$57.1 billion in 2018 [14]. In the United States, the Institute of Medicine estimated that the annual cost of chronic pain, including medical costs and lost productivity, was US \$560 billion to US \$635 billion in 2010 [15]. In Germany, chronic pain was estimated to cost at least US \$63.7 billion annually [16]. At the same time, the care situation for people with chronic pain is characterized by a shortage of health care specialists, resulting in an inadequate supply of treatments [17], particularly of psychotherapy [18]. In contrast, the guidelines for chronic pain explicitly recommend interdisciplinary multimodal pain management, including cognitive and psychological interventions [19].

Virtual reality (VR) is a relatively new nonpharmacological modality to help people suffering from chronic pain, which can also help to improve the care situation [20]. VR treatment for people with chronic pain includes VR games, mindfulness-based interventions, practical exercises, and visual illusions [21]. A meta-analysis showed large effects of VR interventions on pain (standardized mean difference [SMD] 1.6, 95% CI 0.83-2.36) and body functioning (SMD 1.4, 95% CI 0.13-2.67) in people with chronic pain [21]. Although the mechanisms underlying the observed benefits of VR for chronic pain are not yet fully understood, distraction of the patient and embodiment have been discussed as possible explanations for changes in outcomes [20]. Distraction is based on the limited capacity of people to simultaneously attend to different stimuli [22]. It is assumed that attention that would normally be focused on pain is redirected to the VR experience, thereby reducing or eliminating the perception of pain [23]. Embodiment describes the experience of the virtual body in virtual space and can lead to a change in the perception of the physical body and the body matrix, which can have a positive effect on pain perception and physical activity in people with chronic pain [24]. Other mechanisms, including the gamification of exposure to feared movements through the VR [25] and accelerated time perception in VR [26], have also been proposed to have an influence on chronic pain.

VR can therefore be seen as a promising therapeutic option for people with chronic pain. However, there has been no large-scale implementation of this technology in the health care of people with chronic pain. Previous research has shown that organizational structures and the VR technology itself are barriers to the implementation of VR interventions in various health care settings [27-29]. Regarding the use of VR in physiotherapy, due to technical limitations, lack of protocols

for VR interventions, and patient-related factors, VR itself seems to be the main barrier [30]. Conversely, staff and health care professionals may act as facilitators, as they reduce the anxiety of new technologies and can change patients' attitudes toward VR. Health care professionals are also generally interested in using VR in rehabilitation [28-30]. However, people with chronic pain are a group with unique characteristics and diverse impairments, as they may experience pain-related fears and fear of movement, and often have maladaptive coping strategies, mental disorders such as depression or anxiety [31], or cognitive impairments [32]. Since these factors may influence the implementation of VR interventions, it is essential to identify barriers and facilitators for this population in using VR to derive a targeted implementation strategy.

A systematic implementation strategy is necessary to enable large-scale successful implementation and use of VR interventions for people with chronic pain. This requires a comprehensive review of all known barriers and facilitators. The Theoretical Domains Framework (TDF) offers an approach to systematically examine barriers and facilitators toward the development of an implementation strategy [33]. The TDF is an implementation framework for behavioral change that incorporates 128 theoretical concepts derived from 33 different behavior change theories and organizes them into 14 domains into which the barriers and facilitators can be classified [33]. The findings gained in this way can be used to support implementation efforts. For example, this approach was used to support the implementation of stratified care for people with nonspecific low back pain in Canada [34], and was also used to inform the development and implementation of digital tools in a bariatric surgery service [35].

Therefore, the aim of this scoping review was to systematically identify and categorize barriers and facilitators to the implementation of VR interventions for people with chronic pain. The identified barriers and facilitators will provide a basis for recommendations for the successful integration of VR interventions into clinical practice, future development of VR interventions, and future implementation studies in the field of chronic pain management.

Methods

Study Design and Registration

A scoping review was conducted to comprehensively search and synthesize the published literature on barriers and facilitators reported by patients and health care professionals in implementing VR interventions for the treatment of people with chronic pain. The methodological background for this scoping review is based on the five steps outlined by Arksey and O'Malley [36] and the methodological guidance for conducting scoping reviews published by the Joanna Briggs Institute [37]. Reporting follows the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) guidelines; the PRISMA-ScR checklist can be found in [Multimedia Appendix 1](#) [38]. The scoping review was registered with the Open Science Framework [39].

Search Strategy, Eligibility Criteria, and Selection of Evidence Sources

A database-specific literature search was conducted in the electronic databases MEDLINE (through PubMed), Cochrane Central Register of Controlled Trials, CINAHL, PEDro, LILACS, and Web of Science on November 1, 2022. A search strategy was developed using the keywords “chronic pain,” “virtual reality,” and “implementation.” The detailed search string for each database can be found in [Multimedia Appendix 2](#). Additionally, one reviewer (AE) screened the reference lists of the included studies.

The search results were combined and uploaded to CADIMA, a web application that assists in conducting and documenting the evidence synthesis process [40], which we used for the selection process. After removing duplicates, two authors (AE and ML) independently screened the titles and abstracts of identified publications.

The initial inclusion criteria for publications were: (1) use of quantitative, qualitative, or mixed method study designs; (2) involves people with any type of chronic pain; (3) the treatment was a VR intervention; (4) published in the English or German language; and (5) reported implementation outcomes. The exclusion criterion was studies involving children (aged <18 years).

Two reviewers (AE and ML) tested the inclusion and exclusion criteria by screening the titles and abstracts of a random sample of 25 publications to ensure consistent use. If agreement was below 75%, the criteria were adjusted [41]. After title and abstract screening, the reviewers (AE and ML) discussed refining the criteria for full-text screening. As a result, the criterion to include only studies that specifically reported barriers or facilitators as reported by patients or health care professionals as implementation outcomes was added. Barriers were defined as any factors that inhibit or negatively influence patients' use of a VR intervention. Facilitators were defined as all factors that enhance or positively influence patients' use of a VR intervention. Barriers and facilitators had to be self-reported by patients or health care professionals. The two reviewers (AE and ML) independently screened the full texts. Disagreements throughout the review process were resolved by discussion between the two reviewers.

Data Charting Process

One reviewer (AE) extracted the data into a custom data template created for the purpose of this scoping review (see

[Multimedia Appendix 3](#)). A second reviewer (ML) reviewed all extracted data and commented on discrepancies, which were resolved through discussion. We extracted study characteristics (title, authors, year of publication, design, population, and sample size), intervention characteristics (setting, type of intervention), and barriers and facilitators (separately for patients and health care professionals). From qualitative studies, all barriers and facilitators reported by patients or health care professionals were extracted. For quantitative studies, barriers and facilitators were extracted if $\geq 50\%$ of participants agreed that this factor had an influence on the implementation of VR interventions [42].

Collating, Summarizing, and Reporting

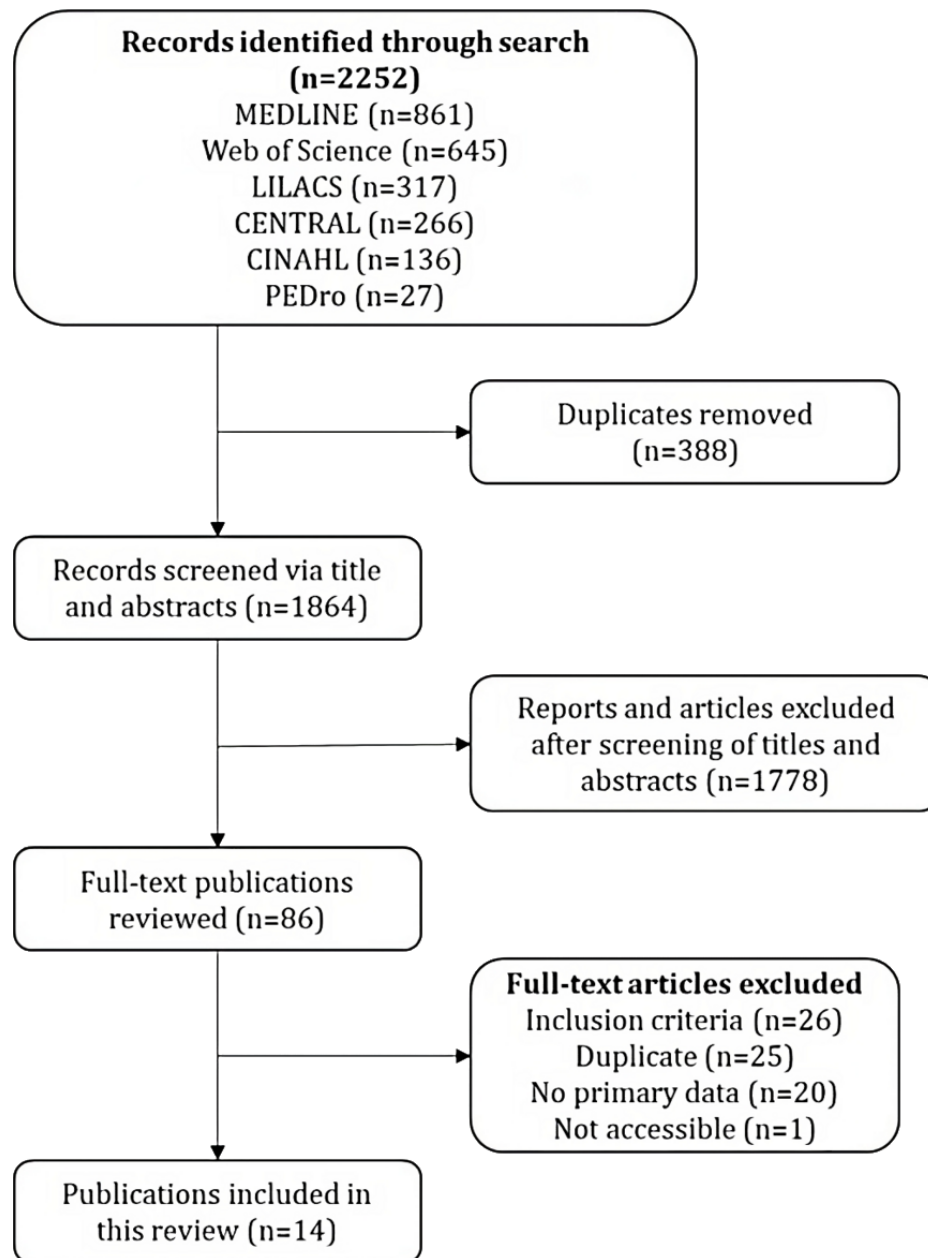
The resulting data were transferred into MAXQDA Plus 2022 (VERBI software, 2021) to code and categorize the barriers and facilitators separately for patients and health care professionals according to the domains of the TDF (see [Multimedia Appendix 4](#)). After coding of the barriers and facilitators by two reviewers (AE and ML), inconsistencies were resolved through discussion. Extracted barriers and facilitators could be categorized in more than one domain.

After evaluation of the number of barriers and facilitators assigned to each domain of the TDF, separately for patients and health care professionals, the most common barriers and facilitators were analyzed to determine underlying themes.

Results

Study Selection

The database search resulted in 2252 publications. After removal of 388 duplicates, 1864 titles and abstracts were screened. Of those, 86 publications met the inclusion and exclusion criteria and were subject to screening of the full text. Among these 86 publications, 72 were excluded because they did not meet the inclusion criteria, were duplicates, did not provide primary data, or were not accessible. Duplicates occurred again in the screening of full texts because the initial removal of duplicates before the screening of titles and abstracts was based solely on the DOI. However, some publications were not recognized by CADIMA in this step due to missing DOIs. Finally, 14 studies were included in the qualitative analysis. The entire selection process is shown in the PRISMA-ScR flowchart in [Figure 1](#).

Figure 1. Flowchart of search and screening results.

Description of Included Studies

Of the 14 studies, there were 8 mixed methods studies [43-50], four qualitative studies [51-54], and two quantitative studies [55,56]. All studies reported barriers and facilitators from the patient perspective, whereas one study also reported barriers and facilitators from the health care professional perspective [53]. The included studies were published between 2013 and 2022, with 9 studies published in 2020 or later [43-46,51-53,55,56]. The sample size of the studies ranged from 7 [49] to 84 [50] participants, with the mean age ranging from 35.86 [49] to 81.85 [55] years. The studies included various VR interventions such as a 5-minute nature relaxation video [46], physically active tasks [43], and specifically developed interventions with guided exercises for focused attention and open awareness [50]. For more information on the

characteristics, study settings, and VR interventions of the included studies, please refer to [Multimedia Appendix 5](#) [43-56].

Overview of Identified Barriers and Facilitators

A total of 65 barriers and facilitators were identified. Among these, there were 30 (46%) barriers and 33 (51%) facilitators from the patient perspective and 2 (3%) facilitators reported from the health care professional perspective. All identified barriers and facilitators are summarized for each TDF domain in [Multimedia Appendix 6](#).

Barriers From the Patient Perspective

The 30 barriers identified from the patient perspective were categorized into six different TDF domains ([Table 1](#)). The other eight TDF domains did not address the barriers identified from the patient perspective.

Table 1. Barriers and facilitators from the patient perspective assigned to Theoretical Domains Framework (TDF) domains.

| TDF domains | Barriers (n=30), n (%) | Facilitators (n=33), n (%) |
|---|------------------------|----------------------------|
| Environmental context and resources | 18 (60) | 6 (18) |
| Skills | 5 (17) | 1 (3) |
| Memory, attention, and decision processes | 2 (7) | 0 (0) |
| Emotion | 2 (7) | 6 (18) |
| Beliefs about consequences | 1 (3) | 10 (30) |
| Reinforcement | 0 (0) | 4 (12) |
| Knowledge | 0 (0) | 2 (6) |
| Behavioral regulation | 0 (0) | 2 (6) |
| Optimism | 0 (0) | 1 (3) |
| Beliefs about capabilities | 0 (0) | 1 (3) |

One of the two most important domains was the *environmental context and resources* (ECR) domain, which included the most barriers from the patient perspective. Three main themes emerged (Table 2). The first was related to the VR devices themselves, with barriers such as the devices being too heavy, too expensive, not detecting all movements, and problems when people with chronic pain were wearing glasses. Furthermore, insufficient support during implementation was perceived as a barrier. The second theme was that the VR software made people with chronic pain feel sick or caused more pain. In addition,

the tutorial of the software was considered to be too difficult. Finally, notable events included technical problems, problems with use due to physical impairments, and patients being in too much pain to use.

Within the domain *skills*, we identified two main barrier-related themes: (1) gaming skills, as the software was too difficult to use and patients without previous experience in playing video games had difficulties controlling the game; and (2) other skills, in which the main barrier was language if the patient's first language was not the same language as that used in the software.

Table 2. Main barrier-related themes from the patient perspective according to Theoretical Domains Framework domains.

| Themes | Quote/description | References |
|--|---|--------------------|
| Environmental context and resources | | |
| VR ^a devices | "A negative factor was that the VR glasses were heavy to wear" | Glavare et al [45] |
| VR software | "Yeah, that would really have to be under guidance, yeah. [...] So they [peers] wouldn't be able to do it alone" | Stamm et al [52] |
| Notable events | "I've got really bad arthritis too at the moment so holding onto those [hand controls] was an issue" | Kelly et al [51] |
| Skills | | |
| Gaming skills | "I had some trouble figuring out which controls to use to move around so um I've never played computer games before and maybe that had something to do with it. I felt like a total idiot totally frustrated and not able to catch onto what to do" | Garrett et al [48] |
| Other skills | The exceptions were those whose first language was not English and who described difficulties in understanding game instructions | Tuck et al [43] |

^aVR: virtual reality.

Facilitators From the Patient Perspective

The 33 facilitators were assigned to nine different domains of the TDF (Table 1). No facilitators were assigned to the other five domains of the TDF.

The most frequently identified facilitators were categorized in the domain *beliefs about consequences*. A closer look at this domain revealed the following three main themes: (1) positive expectations in regard to therapy effects, (2) the VR interventions are helpful for rehabilitation, and (3) the VR

interventions support doing therapy regularly (Table 3). Among the positive expectations for treatment effects, pain, feelings of anxiety and depression, as well as expectations that VR interventions are superior to conventional therapy were mentioned as facilitators. VR interventions were reported to be helpful for rehabilitation because they improved the mood, well-being, and concentration of people with chronic pain. Similarly, people with chronic pain stated that using VR interventions would increase their adherence with the health behavior and that they would use it on a regular basis.

Table 3. Main facilitator-related themes from the patient perspective according to Theoretical Domain Framework domains.

| Themes | Quote/description | Reference |
|--|---|----------------------|
| Beliefs about consequences | | |
| Positive expectations | “I had really high hopes...I thought it might actually take my pain away” | Tuck et al [43] |
| Helpful for rehabilitation | “I’ve taken opiates for 40 years and they don’t work as well as what the virtual reality did” | Kelly et al [51] |
| Increase adherence | “Especially in the future, you could have thousands of different situations that you could immerse yourself in, for as much time as you want in the day” | Garrett et al [53] |
| Environmental context and resources | | |
| VR ^a devices | Several participants noted that flexibility in the position of use and brevity of time in the experience had helped manage or entirely avoid such discomfort: “I’m not in as much pain when I’m seated as when I’m standing, so it was quite easy for me to do the movements” | Kelly et al [51] |
| Supervising therapist | “I think it makes you feel better that it’s a trained physiotherapist. You knew they had that background and it just fills you with confidence a bit more” | Tuck et al [43] |
| Gamification | “Positive factors were that VR added a dimension of playfulness and gaming to the exercise” | Galavare et al [45] |
| Emotion | | |
| Fun and enjoyment | The competition against the computer opponents increased engagement and several participants mentioned the feeling of satisfaction they got when they performed well | Mortensen et al [54] |
| Novel and unknown experiences | “you’re enjoying yourself, you can do things you’ve never experienced before, obviously you’re going to do it” | Kelly et al [51] |

^aVR: virtual reality.

One of the second most frequently identified facilitators was ECR, with three main themes: (1) VR devices, (2) a supervising therapist, and (3) gamification. The VR devices serve as a facilitator because they are simple to use for people with chronic pain, easily adjustable, and can be used in different positions. Similarly, a supervising therapist is considered to facilitate the implementation of a VR intervention. The gamification of therapy through VR interventions was also perceived as a facilitating factor by people with chronic pain.

The second most frequently identified facilitator was classified under the *emotion* domain of the TDF. Within this domain, two main themes were derived: (1) fun and enjoyment, in which people with chronic pain reported that VR interventions triggered positive emotions and evoked a high level of satisfaction; and (2) novel and unknown experiences that the people with chronic pain are not able to experience in the real world.

Facilitators From the Health Care Professional Perspective

Only two facilitators from the health care professional perspective were identified, which were assigned to the domains *ECR* and *beliefs about consequences*. Health care professionals indicated that the opportunity to be with the patient during the VR intervention and to be able to intervene in adverse events supports its implementation. Another facilitating factor from the health care professional perspective was that the VR

intervention allows patients to practice everyday situations in therapy, such as working in the garden.

Discussion

Overview

The aim of this scoping review was to identify and categorize barriers and facilitators associated with the implementation of VR interventions for people with chronic pain, using the TDF. From the 14 included studies [43-56], a total of 65 barriers and facilitators from the patient perspective and two facilitators from the health care professional perspective were identified. The main barriers from the patient perspective to use VR interventions for chronic pain were assigned to the domains *environmental context and resources* and *skills*. However, the domains *ECR*, *beliefs about consequences*, and *emotions* also included facilitators that increased the use of VR interventions from a patient perspective. Health care professional perspectives are poorly researched, with only one study [52] found on this topic. To our knowledge, this is the first scoping review summarizing barriers and facilitators to the implementation of VR interventions for people with chronic pain.

Selection of a VR Device

At first glance, a contradictory result of this study is that the *ECR* domain includes barriers as well as facilitators to the implementation of VR interventions for chronic pain. However, since VR devices and VR software emerged as major themes within the barriers and facilitators in this domain, an important

step in implementing VR interventions appears to be the selection of an appropriate VR device and VR software for patients with chronic pain and in consideration of their actual conditions. This decision may be particularly important for people with chronic neck pain, as they may be more sensitive to the weight of VR devices, which could lead to an increase in pain [49]. Although future technological developments of VR devices with lower weight might improve this limitation, the use of VR devices for people with chronic neck pain will remain an individual decision depending on individual tolerance. If these steps are taken carefully, it is possible that the chosen VR device and the VR intervention itself will act as a facilitator in the implementation process. These findings support three proposed aspects to be considered when preparing a VR therapy: the right VR intervention at the right time and with the right patient [57]. These findings are consistent with published recommendations to adopt a participatory approach involving the patients themselves throughout the development process of VR interventions to consider all of the above aspects at an early stage [58].

VR Skills

A second important TDF domain including barriers was *skills*, relating specifically to the patient's gaming skills and language skills. Both can be addressed in software development, such as by participatory developed tutorials or using plain language. These recommendations are partly reflected in the recommendations for the participatory development of VR interventions [58] and are also in line with a previous review, which argued for providing sufficient time to learn and use the new technology for patients and health care professionals [27]. However, our findings emphasize the importance of developing and providing plain-language options in VR interventions for people with chronic pain, potentially due to their shorter attention spans and greater susceptibility to interruption [59], as well as other mental health concerns such as psychological distress [11], anxiety, and depression [31]. For existing interventions, these barriers can be addressed with an implementation strategy. As part of such a strategy, special attention should be given to competencies of health care professionals related to the use of VR to enable them to teach the acquired skills to their patients with individual needs [29]. Additionally, for a successful implementation, it is important that health care professionals are positive about the digital technology [60] and perceive it as user-friendly [61]. Thus, a key aspect of implementing VR in the treatment of chronic pain is adequate training of the health care professionals who will provide the VR interventions to people with chronic pain.

No barriers in regard to game design quality, such as poor graphics or boring games, were reported by people with chronic pain or health care professionals, which was a somewhat surprising finding. Considering the publication dates of the literature retrieved and our own experience with VR interventions, it would have been conceivable that the grade of immersion or perceived difference between the virtual world and the real world could still be experienced as a barrier to using VR interventions.

VR Treatment Expectations

Existing positive expectations regarding pain improvement and rehabilitation facilitate the implementation of VR interventions for people with chronic pain [43,51,53,55,56]. A positive belief in VR interventions seems to result in more satisfaction with the outcome of therapy in general [30] and has an impact on cooperation and outcomes in people with chronic pain in general [62]. When implementing VR interventions for people with chronic pain, this positive belief can be used and facilitated by educating patients about the positive effects of the intervention and presenting best-practice examples.

Another theme that emerged within the domain beliefs about consequences is that VR interventions could increase treatment adherence because VR helps people with chronic pain to improve health behaviors and their ability to focus on tasks [56]. In addition, patients see the possibility that in the future they will be able to choose from many different virtual scenarios in which they can immerse themselves to help with their pain [53].

Lack of patient adherence is a common problem associated with poorer treatment outcomes [63,64] and VR may be a viable option to reduce this problem. Our results are in line with a previous review, which showed that VR can encourage patients to adhere to treatment [30]. VR and its potential impact on adherence may facilitate high-intensity therapy and thereby improve outcomes, as a network meta-analysis showed that high-intensity therapy in particular can have a positive impact on outcomes in chronic pain therapy [65].

The themes fun and enjoyment and having novel experiences provide an explanation for the above-mentioned good adherence to VR interventions. The ability of VR to provide novel experiences for people with chronic pain has also been highlighted in other studies [30]. Furthermore, positive emotions such as fun and enjoyment may themselves have a positive impact, considering that negative emotions are a risk factor for the development and maintenance of chronic pain [66].

Perspective of the Health Care Professionals

In our scoping review, we were only able to identify one study that focused on facilitators from the perspective of health care professionals, who naturally play a crucial role in the implementation of digital interventions [60]. Health care professionals mentioned that VR is a good opportunity to treat people with chronic pain in everyday situations and that they want to be close to the patients during the treatment [53].

Integration With Existing Literature

When comparing the findings of this review with findings from other reviews looking at the implementation of VR interventions in various health care settings [29], rehabilitation [27], and physical therapy [30], it is notable that the identified themes differ only in terms of the details and cover mostly similar topics such as the barrier of appropriate VR interventions and VR devices for the individual patient, as well as the facilitators of having a strong belief in the efficacy of these interventions. This preliminary finding suggests that implementing VR interventions for people with chronic pain is not fundamentally different from implementation in other settings; however, due

to the nature of chronic pain, cognitive and functional impairments should be taken into account. Additionally, since the health care professional perspective is not fully understood, further research on this aspect is necessary.

Limitations

One limitation of this scoping review is that classification of barriers and facilitators into TDF domains may be subjective, although we aimed to minimize subjectivity by standardized procedures using a coding guideline based on TDF domains with two independent reviewers. In this scoping review, barriers and facilitators were ranked according to how often they were mentioned in the included studies. However, this may not necessarily reflect their importance. Barriers and facilitators mentioned only once may nevertheless be the most important factor in a particular implementation setting. In particular, barriers and facilitators in quantitative studies were included if they had more than 50% agreement in the study, whereas all barriers and facilitators mentioned in qualitative studies were included. This may impact the distribution of barriers and facilitators.

The review process did not include a critical appraisal of the studies; although this is not standard practice for scoping reviews, it might be considered a limitation regarding the quality of the evidence. Furthermore, only studies published in German

or English were included. This may limit conclusions about implementation in other countries.

Recommendations

Our findings provide a comprehensive overview of the barriers and facilitators to implementing VR interventions for people with chronic pain in the existing literature. Based on the identified barriers, the development of VR devices and VR interventions should address the perspectives of both people with chronic pain and health care professionals. This could reduce language, cognitive, or physical barriers that are important for patients with specific impairments.

Based on the identified barriers and facilitators, systematic and targeted implementation strategies for VR interventions for people with chronic pain can be developed. For example, the barrier of lack of skills can be reduced by offering targeted training to health care professionals, and positive expectations of VR interventions can be reinforced, such as by displaying a poster about the positive effects of VR in the waiting room. In addition, future research on VR interventions and implementation should pay more attention to the perspective of health care professionals to gain better insight into the values and needs of these critical stakeholders. This can be achieved through an implementation study that includes a formative evaluation of the implementation steps with a focus on health care professionals and their experiences in the process.

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Data Availability

The data sets generated and analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

AE, AGS, and CK contributed to conceptualization. AE developed the search strategy and conducted the search. AE and ML screened titles and abstracts and the full text, extracted the data, and categorized the data into domains. AE summarized the domains. AE wrote the original draft; manuscript review and editing were performed by all authors (most notably AGS and CK).

Conflicts of Interest

None declared.

Multimedia Appendix 1

PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) checklist. [[DOCX File, 46 KB - xr_v1i1e53129_app1.docx](#)]

Multimedia Appendix 2

Search strategy.

[[DOCX File, 15 KB - xr_v1i1e53129_app2.docx](#)]

Multimedia Appendix 3

Data extraction sheet.

[[XLSX File \(Microsoft Excel File\), 11 KB - xr_v1i1e53129_app3.xlsx](#)]

Multimedia Appendix 4

Description of domains in the Theoretical Domains Framework.

[\[PDF File \(Adobe PDF File\), 83 KB - xr_v1i1e53129_app4.pdf \]](#)

Multimedia Appendix 5

Description of the included studies.

[\[DOCX File, 23 KB - xr_v1i1e53129_app5.docx \]](#)

Multimedia Appendix 6

Summary of all identified barriers and facilitators according to Thematic Domains Framework domains.

[\[XLSX File \(Microsoft Excel File\), 11 KB - xr_v1i1e53129_app6.xlsx \]](#)**References**

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Abbreviations

ECR: environmental context and research

PRISMA-ScR: Preferred Reporting Items of Systematic Reviews and Meta-Analyses extension for Scoping Reviews.

SMD: standardized mean difference

TDF: Theoretical Domains Framework

VR: virtual reality

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Editorial

Discovering and Creating the Leading Edge of Extended Reality and Spatial Computing: A Message From the Editor-in-Chief

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Abstract

We are pleased to introduce *JMIR XR and Spatial Computing*, a peer-reviewed journal dedicated to advancing the integration of extended reality and spatial computing technologies into routine clinical care.

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KEYWORDS

editorial; extended reality; XR; spatial computing

We are excited to announce the launch of *JMIR XR and Spatial Computing*, a peer-reviewed journal dedicated to showcasing research on extended reality (XR) and spatial computing technologies and their integration into everyday clinical practice.

In navigating the frontier of XR and spatial computing for more than a decade, we have adopted a stance of informed optimism tempered by vigilant caution. Based on the large number of high-quality articles published by JMIR Publications and others over the last decades, the tremendous potential of these technologies to enhance diagnostic precision, increase treatment efficacy, facilitate easier access to care, and—most importantly—improve patient outcomes seem obvious. Yet, we remain cognizant that their integration into the health care ecosystem is not without peril and may take longer than many researchers and technologists have expected. We anticipate that immersive technologies will transition from a novel solution to an established standard in targeted medical scenarios. However, integration into complex health care systems and widespread acceptance by health care workers will not happen overnight. Not unlike other established technologies, we expect a slow and stepwise adoption as a result of candid discussions within the community, and rigorous, basic, translational, and clinical research [1].

XR and spatial computing are relatively old concepts, dating back to at least the late 1960s; they became visible to the scientific community through iconic works such as Ivan Sutherland's *The Sword of Damocles* [2]. In 2003, Simon

Greenwold at the Massachusetts Institute of Technology described “spatial computing” in his thesis as a “human interaction with a machine in which the machine retains and manipulates referents to real objects and spaces” [3]. Inspired by prior researchers and technologists, he foresaw that “the augmentation of a data network with a physical network promotes the flow of digital information on top of existing social interactions” [3].

When JMIR Publications launched in 1999, the widespread adoption of XR and spatial computing in clinical settings was hard to imagine. Fast forward to today, and we find ourselves at the cusp of an era where XR and spatial computing are poised for integration into routine clinical care. This shift has been propelled by a confluence of recent technological advancements. The rapid artificial intelligence (AI) evolution [4], particularly breakthroughs in computer vision, has significantly improved spatial mapping and 3D scene understanding. Furthermore, AI has truly revolutionized programming code and 3D content creation. Exponential improvements in graphical processing capabilities [5] have been complemented by significant advances in lightweight, energy-efficient display technologies [6], and the advent of high-bandwidth and low-latency networks has significantly enhanced connectivity. The decreasing costs of XR technology and its growing popularity among consumers continue to lower adoption barriers for XR and spatial computing in health care.

The tangible impact of these developments in health care is evident. For instance, Bandelow et al [7], who authored the German guideline for treating anxiety disorders, recommend virtual reality exposure therapy as a viable alternative when in vivo exposure is not feasible for patients with spider, height, or flight phobias. Furthermore, the US Food and Drug Administration has reviewed and authorized the marketing of a growing number of devices with augmented reality and virtual reality through 510(k) clearance, De Novo requests, or premarket approval in many fields of medicine [8].

These examples illustrate the growing acceptance of immersive technologies in clinical practice as “another arrow in the quiver” of health care.

However, our optimism is tempered with pragmatism. Although XR and spatial computing offer promising avenues for enhancing health care delivery, we recognize that they are not universal solutions. The successful integration of these technologies into existing health care systems and workflows requires thoughtful consideration and careful implementation [8]. Their true effectiveness will be determined by the appropriateness of their application, the specific contexts in which they are deployed, a significantly positive cost-benefit ratio, and most importantly, their demonstrable ability to improve patient outcomes or enhance health care efficiency [8,9]. As we move forward, it is crucial to approach the adoption of these technologies with a balanced perspective, ensuring that their integration complements and enhances, rather than disrupts, the foundational aspects of quality health care delivery.

Therefore, we encourage authors from both academia and industry to view *JMIR XR and Spatial Computing* as a platform for showcasing their collaborative efforts, sharing insights, and

contributing to the responsible advancement of immersive technologies in health care.

Our journal recognizes the critical importance of addressing the accessibility and equity challenges surrounding XR and spatial computing technologies. We strongly encourage the community to submit manuscripts exploring innovative solutions to these pressing issues. We are particularly interested in studies on cost-effective technology implementations in resource-limited settings and strategies for overcoming infrastructure barriers in underserved areas. By fostering dialogue and research in this area, we aim to ensure that the transformative potential of XR and spatial computing technologies benefits the entire international community.

Central to our vision is the belief in the power of strong academic-industrial collaborations. These collaborations bridge the gap between theoretical research and practical application, accelerating the development of cutting-edge XR and spatial computing solutions while ensuring they meet rigorous scientific standards. Therefore, we actively encourage and facilitate partnerships between academic researchers and industry innovators. Furthermore, we invite independent, nonacademic developers and designers as well as open-source project contributors of all kinds to communicate their perspectives with us. We believe that the transparency and accessibility of open-source development can significantly accelerate progress in XR and spatial computing applications for health care.

By embracing contributions from this diverse range of sources—academic-industrial collaborations, individual innovators, and open-source communities—we aim to foster a rich ecosystem of ideas and developments that will shape the future of XR and spatial computing in health care.

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Conflicts of Interest

LR is the editor-in-chief of *JMIR XR and Spatial Computing*. He is also a stakeholder in Shift Medical GmbH.

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Abbreviations

AI: artificial intelligence

XR: extended reality

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Original Paper

Using Virtual Reality to Reduce Stress in Adolescents: Mixed Methods Usability Study

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Abstract

Background: Adolescent mental health is a national mental health emergency amid surging rates of anxiety and depression. Given the scarcity and lack of scalable mental health services, the use of self-administered, evidence-based technologies to support adolescent mental health is both timely and imperative.

Objective: The goal of this study was 2-fold: (1) to determine the feasibility, usability, and engagement of a participatory designed, nature-based virtual reality (VR) environment and (2) to determine the preliminary outcomes of our self-administered VR environment on depression, mindfulness, perceived stress, and momentary stress and mood.

Methods: We conducted a within-person, 3-week, in-home study with a community-based sample of 44 adolescents. Participants completed surveys of perceived stress, depression, cognitive fusion, and mindfulness at intake, postintervention, and a 3-week follow-up. Participants were invited to use a nature-based, VR environment that included 6 evidence-based activities 3 to 5 times per week. They completed momentary stress and mood surveys 5 times each day and before and after each VR session. Postintervention, participants completed surveys on system and intervention usability and their experiences with using the VR system. Quantitative data were analyzed using descriptive statistics and mixed effects modeling to explore the effect of the VR environment on stress. Qualitative data were analyzed using collaborative thematic analysis.

Results: Participants' use of the VR environment ranged from 1 session to 24 sessions (mean 6.27 sessions) at home over a 3-week period. The 44 participants completed all study protocols, indicating our protocol was feasible and the VR environment was engaging for most. Both the use of the VR system and novel VR intervention received strong usability ratings (mean 74.87 on the System Usability Scale). Most teens indicated that they found the tool to be easily administered, relaxing, and helpful with stress. For some, it offered space to process difficult emotions. The themes *calm*, *regulating*, and *forget about everything* resulted from open-ended exit interview data. Although the Relaxation Environment for Stress in Teens (RESeT) did not significantly affect repeated survey measurements of depression, mindfulness, nor cognitive fusion, it did positively affect momentary mood (pre-intervention: 10.8, post-intervention: 12.0, $P=.001$) and decrease momentary stress (pre-intervention: 37.9, post-intervention: 20.6, $P=.001$). We found a significant reduction in within-day momentary stress that strengthened with increased VR use over time during the study period ($P=.03$).

Conclusions: These preliminary data inform our own VR environment design but also provide evidence of the potential for self-administered VR as a promising tool to support adolescent mental health. Self-administered VR for mental health may be an effective intervention for reducing adolescent stress. However, understanding barriers (including disengagement) to using VR, as well as further encouraging participatory design with teens, may be imperative to the success of future mental health interventions.

KEYWORDS

virtual reality; adolescents; perceived stress; participatory design; depression

Introduction

It is good to like, to have the brain stop for a second and focus on small things. [P98, girl, 16 years old, exit interview]

The Potential for Virtual Reality in Adolescent Mental Health

In a 2018 American Psychological Association survey [1], teens reported worse mental health and higher levels of anxiety and depression than all other age groups. Increased stress causes adverse mental and physical outcomes, including anxiety and depression [2]. However, despite effective, evidence-based treatments for adverse outcomes associated with stress [3], only one-half of teens will receive mental health services due to mental health provider shortages and other barriers to accessing care [4,5]. Even worse, evidence-based therapies are often inaccessible due to cost, time, or the need for a trained interventionist [6]. Therefore, a self-administered, technology-based solution could increase accessibility and scalability of these therapies.

Virtual reality (VR)-based serious games (SGs) for mental health present an opportunity for the translation of effective mental health strategies to an engaging platform [7,8]. VR consists of a head-mounted display that displays simulated environments for exploration and interaction. The immersive and intuitive experience of VR makes it an optimal platform for delivering self-administered SG health interventions for adolescents [9]. Additionally, VR-based SGs are scalable, which could increase accessibility to evidence-based mental health care. VR has been successfully deployed in treating an array of health conditions in adults, including posttraumatic stress disorder [10], phobias [11], and perceived stress in military personnel [12].

The use of VR as an intervention platform for adolescent mental health is an emerging area of inquiry [13,14]. VR has been shown to be acceptable and effective in treating procedural pain, headaches, and public speaking anxiety in adolescents [15-18]. In addition, Björ ling et al [19] found that a nature-based environment reduced stress in teens and that teens will self-administer VR therapeutically. Building on these findings, it has been suggested that existing evidence-based mental health therapies, such as cognitive behavioral theory (CBT), could be translated into a VR environment as an innovative approach to delivering scalable mental health interventions [20]. Although a recent systematic review of clinical trials of mostly computer-based video games found CBT SGs to be more effective than no intervention, true efficacy was clouded by study rigor, and none of the CBT games were VR [21]. In a systematic review of VR environments intended to reduce pain and anxiety in children and adolescents, Ahmadpour et al [22] proposed that future VR interventions explore skill building

and provide dynamic feedback to participants to enable them to be an active participant in managing their own care.

The Importance of Participatory Design

Participatory design (PD) is an approach in which the people who are “destined to use the system play a critical role in designing it” [23]. In PD, the goal is not to simply build systems that address the needs and wants of people. Rather, the hallmark of PD is to establish cooperative and collaborative design relationships that engage users throughout the iterative design process. Research results are often collaboratively interpreted by designer-researchers and the participants who will use the design. For this very reason, gathering data continually during the design and testing phases of development is essential. Such a collaborative approach is thought to result in solutions that address real-world needs and priorities in people’s lives [24,25].

Engaging teens in PD is rare in the design and development of VR, though it is a successful methodology for working with teens in relation to mental health [26-28]. PD is an appropriate approach for designing new technologies with teens due to its meaningful engagement of participants throughout the design process [29,30]. However, engagement is highly variable, and the methods are often iterative and flexible [26]. Examples of engaging teens in co-design for mental health include suicide prevention through social media [27] and stress reduction via a social robot [28]. In fact, co-design with youth specifically for VR has also shown to be successful. Realpe et al [31] engaged youth in the co-design of a virtual environment as a social cognition intervention for people with a first episode of psychosis. Björ ling et al [32] successfully engaged teens in the design of a VR environment aimed to reduce stress.

Our Motivation: A Study of Usability and Experience

As a technology, VR holds the potential to provide immersive experiences and skills training to reinforce evidence-based mental health practices. However, in order to be effective, it must be engaging and usable by teens. Therefore, we designed and developed our VR environment, Relaxation Environment for Stress in Teens (RESeT), using a human-centered, PD approach. We engaged adolescents in each stage of development to ensure usefulness and maximize engagement. Equally important was to empirically measure usability and user experience. Therefore, in our pilot study of our novel VR environment, we explored 2 aims and associated research questions (RQs).

Aim 1

The first aim was to measure the implementation outcomes (feasibility, acceptability, appropriateness, usability, and engagement) of a participatory designed, nature-based VR environment.

- RQ1: How did teens use RESeT, and how did they rate its implementation?
- RQ2: What is the experience of using RESeT?

Aim 2

The second aim was to determine the preliminary mental health outcomes of our self-administered VR environment on depression, mindfulness, perceived stress, and momentary stress and mood.

- RQ3: What effect does RESeT use have on retrospective stress (Perceived Stress Scale [PSS]), depression (Patient Health Questionnaire 9 [PHQ-9]), cognitive fusion (Cognitive Fusion Questionnaire [CFQ]), or mindfulness (Mindfulness Attention and Awareness Scale [MAAS])?
- RQ4: What effect does RESeT use have on momentary stress and mood?
 - RQ4a: Do baseline depression, mindfulness, and stress moderate the effect of [VR environment] on momentary stress over the 3-week intervention?

- RQ4b: Does dosage (frequency and duration of VR use) moderate momentary stress over the 3-week intervention?

Methods

Study Timeline

The prospective, within-person study design utilized multiple layers of measurement. Participants completed surveys at intake, exit, and follow-up as well as within-day momentary measurements of stress and mood and pre- and post-VR measurements. See [Table 1](#) for a summary of the participant activities and measurement over time.

Table 1. Study measurement timeline.

| Study activity | Research question (RQ) | Intake | 5 times per day during the 3-week intervention | Pre/post-VR ^a use | Exit (at 3 weeks) | Follow-up (at 7 weeks) |
|--|------------------------|--------|--|------------------------------|-------------------|------------------------|
| Survey instruments | | | | | | |
| PHQ-9 ^b (depression) | RQ3 | ✓ | | | ✓ | ✓ |
| PSS ^c (retrospective stress) | RQ3 | ✓ | | | ✓ | ✓ |
| CFQ ^d (cognitive fusion) | RQ3 | ✓ | | | ✓ | ✓ |
| MAAS ^e (mindfulness/attention) | RQ3 | ✓ | | | ✓ | ✓ |
| SUS ^f /IUS ^g (usability) | RQ1 | | | | ✓ | |
| IAM ^h , FIM ⁱ , AIM ^j (appropriateness, feasibility, acceptability of intervention) | RQ1 | | | | ✓ | |
| Interview (user experience) | RQ2 | | | | ✓ | |
| Momentary instruments | | | | | | |
| Stress | RQ4 | | ✓ | ✓ | | |
| Sadness | RQ4 | | ✓ | | | |
| Affect | RQ4 | | | ✓ | | |
| Comfort | RQ4 | | | ✓ | | |

^aVR: virtual reality.

^bPHQ-9: Patient Health Questionnaire 9.

^cPSS: Perceived Stress Scale.

^dCFQ: Cognitive Fusion Questionnaire.

^eMAAS: Mindfulness Attention and Awareness Scale.

^fSUS: System Usability Scale.

^gIUS: Intervention Usability Questionnaire.

^hIAM: Acceptability of Intervention Measure.

ⁱFIM: Feasibility of Intervention Measure.

^jAIM: Appropriateness of Intervention Measure.

The Development of a Relaxation Environment for Teen Stress

The novel VR RESeT was developed in partnership with teens and the Seattle Public Library. Design of RESeT began by eliciting teen ideas and design principles through PD sessions spanning 2 years with approximately 60 teens at local library

sites. Some of our design-session studies are described in a previous publication [32]. Based upon teen preferences, RESeT was designed as an open, explorable world filled with nature, animals, and calming activities. The activities in RESeT incorporate evidence-based mental health activities stemming from dialectical behavioral therapy [33], acceptance and commitment therapy [34], and mindfulness-based stress

reduction for teens [35]. Each of these therapies have been shown to be very effective in adolescents. Although such self-administered exercises are typically administered in workbooks and worksheets, we incorporated them into the immersive and interactive VR world with teens as our co-designers.

As an example, teens experience “defusion” from negative emotions in the VR environment by placing negative words into a paper boat and releasing the boat out onto a river. As the boat floats away from them, they can reflect on their ability to release negative emotions rather than hold them tightly or be “fused” with them. This process is called *cognitive defusion* [36]. Another example in the environment is building a teen’s capacity for mindfulness through an interaction that invites teens to listen carefully for different birds and look to find where their song is coming from. Integrating these activities was iteratively refined through a series of design sessions (37 teens) and usability testing sessions (9 teens) resulting in a fully

functional RESeT comprised of 6 evidence-based interactions. In addition, the game was designed with arm-swing locomotion where the player swings their arms back and forth to create a natural walking pace in VR. The faster they swing their arms, the faster they move through the environment. Not only is this type of locomotion naturalistic, it has also been shown to improve mood [12].

The RESeT is a natural environment set in winter, consisting of a mountainous border surrounding a snow-covered, tree-filled meadow. A river runs through the meadow, providing a natural border to create an open world feeling for player exploration. A riverboat provides players with a relaxing space in which they can explore and participate in various activities without having a time limit or required objective. Nature sounds and ambient music play in the background through the experience.

Players start the game at a home base location in the middle of the map. See Figure 1 for an illustration.

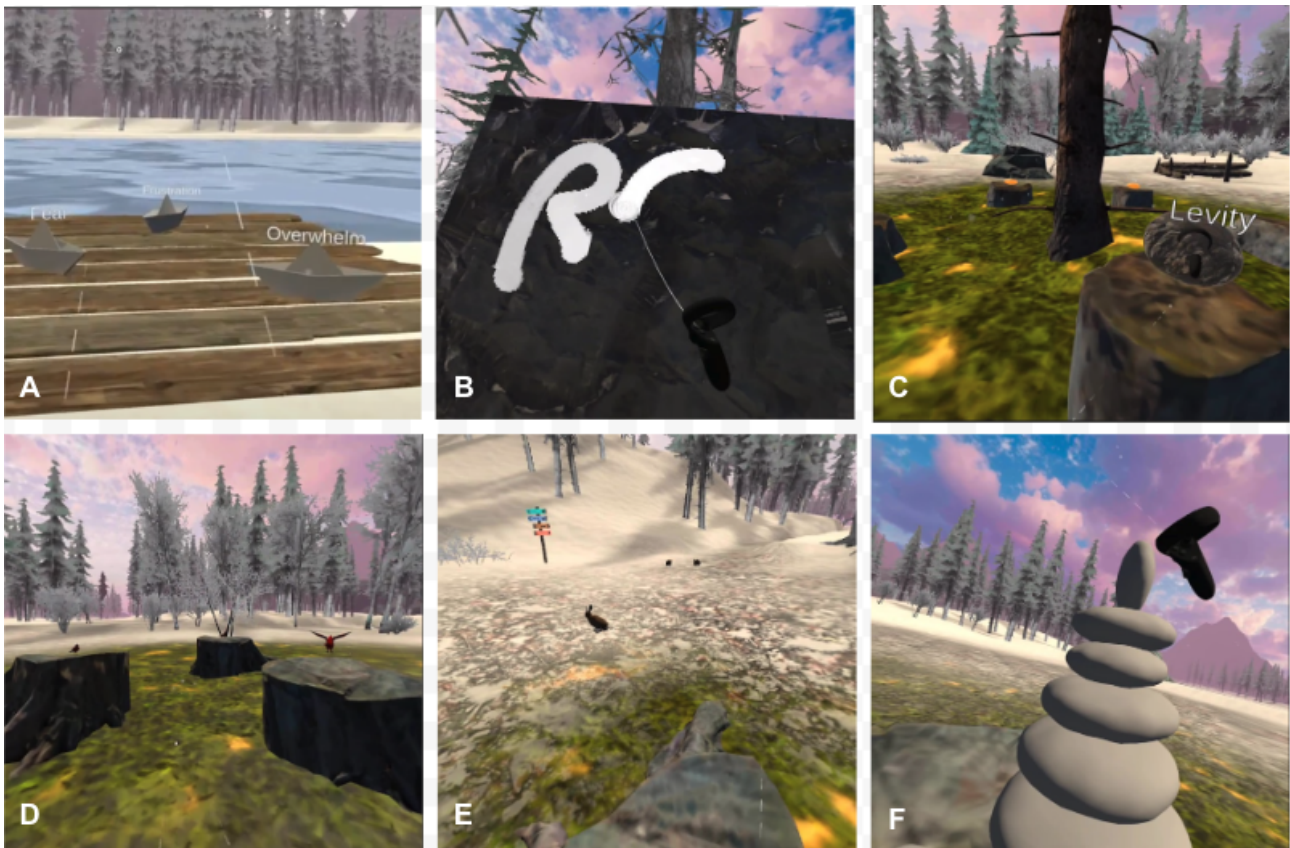
Figure 1. Examples of the (A) controller, (B) wayfinding, and (C) activity navigation.



The environment is designed for seated or standing gameplay using arm-swing navigation intended to feel most like walking. Participants navigate a series of wandering paths and colorful signposts to guide them to 6 clearings, each containing a different activity. See Figure 2 for screenshots during gameplay for each of the 6 activities. In the riverboat activity, players set paper *feeling* boats into the water. Each boat is labeled with a different negative emotion (emotional clarity/cognitive defusion). In the painting activity, players are able to paint on a surface, with their painting slowly disappearing after a short period of time (artful mindfulness). In the scavenger hunt, players search for rocks hidden around the clearing and place

them on stumps when found. Each rock is labeled with a positive word, and when all rocks are found, they change color (visual attention/positive affirmations). With bird search, players search for 3 hidden birds by following the bird’s call. When found, the bird flies to a stump, and when all 3 birds are found, flowers appear (auditory mindfulness). In the rabbit hole activity, players stand still near a stump, and rabbits appear the longer they are standing there (attention/awareness). With rock stacking, players stack rocks on each other to create stacks or other formations (attention/focus). See Multimedia Appendix 1 for a video illustration of the environment.

Figure 2. Screenshots of gameplay illustrating each of the 6 activities: (A) riverboat, (B) painting, (C) scavenger hunt, (D) bird search, (E) rabbit hole, (F) rock stacking.



Ethics Approval

The University of Washington Institutional Review Board approved this study (Study 00003795: Virtual Relaxation Experience).

Recruitment, Screening, and Enrollment

A convenience sample of teens was recruited from April 2021 through June 2021 via social media (Facebook, Twitter), listservs, and snowball sampling. Eligibility criteria included (1) ages 14 years to 18 years, (2) able to speak and read English, (3) have a smartphone with SMS text messaging capabilities, and (4) currently live in the greater metro area. Prospective participants with a diagnosed seizure disorder were excluded from this study due to the risk of VR triggering a seizure.

Research Electronic Data Capture (REDCap) [37], a secure web-based data collection and management system, was used for all participant survey data collection. Prospective participants accessed the REDCap study eligibility screening survey via a QR code or weblink, which described the study aims and associated activities. Eligibility was automatically determined after the individual completed the survey. Those who were eligible were consented within the REDCap system. Participants were informed of the study procedures and phases and that they could disengage at any time. Parents of participants younger than 18 years were sent an email with study contact information.

Upon entering the study, a VR kit was delivered to the participant's home via study staff using a no contact protocol described in a previous study by Sonney et al [38]. Participants

were emailed an enrollment and orientation packet that included a video demonstration of setting up and charging the VR headset. During the study, research staff used text messaging to check in with participants the day they received the VR kit, on day 3, and once a week thereafter. Participants were informed to contact study staff by text if they had any questions.

Instrumentation

Surveys included an investigator-developed questionnaire capturing participant age, grade in school, and prior experience using VR (never, once, 2-5 times, ≥ 6 times) for numerous VR technologies, including standalone headsets, full headsets, and Google cardboard. Participant gender, racial, ethnic, and tribal (if applicable) identities were collected via a write-in option. Standardized surveys focused on implementation outcomes (Aim 1, RQ1) were administered postintervention (Time 2) and included the Acceptability of Intervention Measure, Feasibility of Intervention Measure, Appropriateness of Intervention Measure [39], System Usability Scale (SUS; $\alpha=.85$) [40], and Intervention Usability Scale (IUS) [41]. Surveys focused on mental health outcomes (Aim 2, RQ3) included the PHQ-9 ($\alpha=.89$) [42], PSS ($\alpha=.71-.91$) [43], CFQ ($\alpha=.93$) [44], and MAAS ($\alpha>.80$) [45]. These were administered at intake (Time 1), after the 3-week intervention (Time 2), and 4 weeks postintervention (Time 3). Intake surveys were estimated to take 15 minutes to 20 minutes to complete, and exit surveys were estimated to take 15 minutes to 25 minutes.

Momentary instruments (Aim 2, RQ4) included a 5-time per day momentary survey using SEMA 3 software [46] to gather within-day momentary assessments of stress and mood over the

3-week intervention period. Participants were sent 5 scheduled, within-day mood surveys each day of the 3-week study. Within-day surveys asked 2 questions: “How stressed do you feel right now?” and “How sad do you feel right now?” Participants answered these questions on a sliding scale ranging from no sadness/no stress (0) to extremely sad/extremely stressed (100). In addition, a pre- and post-VR survey was developed that included the same stress scale as the within-day survey. However, it also included an abbreviated Positive and Negative Affect Scale [47] and a comfort scale for post-VR: “How comfortable was your VR session?” (1: not very comfortable to 5: very comfortable). Momentary surveys were estimated to take between 30 seconds and 90 seconds to complete.

Given the potential for participants to forget the self-initiated VR survey, we addressed Aim 1, RQ2 using 2 VR use statistics: VR use frequency (number of sessions) and VR use duration (length of use). These were measured through VR activity metrics downloaded directly from each headset. An analytics system built into RESeT saved a VR use log file with a time stamp and duration for each session. In case the analytics system malfunctioned, the Android OS UsageStatsManager was used to retrieve total app use time from the last 24 hours, 7 days, and 30 days.

Finally, to address Aim 1, RQ2, a semistructured interview examined the participant experience, perceived effect, and feedback related to the protocol and environment (Aim 1). For example, “What did you feel using RESeT?” and “What concerns do you have about using RESeT?” Interviews lasted approximately 15 minutes and were recorded via videoconferencing software. In addition, we asked participants about their likelihood to continue using the environment as well as how they might change the design. The semistructured interview took between 10 minutes and 20 minutes to complete.

Intervention Procedure

Participants were delivered a Quest 2 headset, charger, and customized user manual that included links to troubleshooting and an unboxing video directly to their home. At the start of the study, they were asked to use RESeT for 10 minutes to 15 minutes 3 to 5 times per week. Participants were not further prompted to use the headset nor were they incentivized based upon the amount of headset use during the study. Before each use, they were asked to complete the SEMA presession surveys (stress, affect), explore the RESeT however they desired, and complete the SEMA postsession surveys (stress, affect, comfort). The study team completed weekly check-ins via text message throughout the 3-week pilot and were available for any questions.

At the end of the 3-week pilot, REDCap automatically sent participants the postintervention survey queue, and the study team conducted a semistructured exit interview and scheduled a time to retrieve the VR study kit, which was sanitized and prepared for the next participant. A 3-week follow-up survey queue was automatically sent by REDCap. Participants received digital gift cards after each survey completion. Participants received US \$25 at Time 1, US \$75 at Time 2, and US \$50 at Time 3.

Data Analysis

Quantitative Analyses

All statistical computations were performed in the open-source R software program [48]. Descriptive statistics were used to describe the sample characteristics, survey scores, and intervention use. Longitudinal spaghetti plots were performed to explore time trends and form. A repeated measures ANOVA was conducted to detect group and within-individual differences during survey time points (Time 1-Time 3). Longitudinal mixed effects models with random effects for time, frequency, or duration were computed to detect changes in stress within individuals. A linear regression model with random effects controlled for participant variations was used to measure change in affect and stress resulting from each VR session.

Several models were run to explore whether dosage (number of sessions and duration of use) moderated the change in momentary stress over time. For dosage models, we explored whether changes in stress scores were linear (uniform rate of improvement as dosage increased), quadratic (declining rate of improvement as dosage increased), or cubic (declining and then increasing rate of improvement as dosage increased).

Full maximum likelihood estimation was used, and model building followed a standard procedure [49]. A null model was built first to establish baseline variance for stress over time, followed by longitudinal trend models testing linear, quadratic, and cubic longitudinal trends. These were run on 3 separate sets of models testing longitudinal trends for variables representing number of days since baseline, number of times the VR was used, and number of minutes the VR was used. The best longitudinal trend was selected by model fit deviance statistics using $-2 \log$ likelihood and Akaike information criterion. We tested for possible moderation effects by computing models with each variable and simple interaction between them. Moderation models included possible moderation between stress over time and (1) frequency x duration, (2) baseline PSS, (3) baseline PHQ-9, and (4) baseline MAAS. Significance for moderator terms was determined by t score significance values for covariate estimates.

Post Hoc Groupings

For the purposes of analysis, participants were grouped into depression level and VR use categories based upon their study data. We based 4 mutually exclusive VR use groupings (minimal [<3 sessions], low use [$3-4$ sessions], moderate use [$5-7$ sessions], high use [≥ 8 sessions]) upon their self-administered VR use during the study. Depression levels were assessed using the Time 1 PHQ-9 scores. Participants were grouped into mild ($\text{PHQ-9} < 5$), moderate ($\text{PHQ-9} = 5-9$), and severe ($\text{PHQ-9} \geq 10$) depression levels. We excluded 8 participants from the analyses exploring the effect of the VR environment on surveyed variables (depression, retrospective stress, mindfulness, cognitive fusion) given their low use of the VR headset (<3 sessions). However, all 44 participants were included in the analyses exploring the relationship between VR use and stress over time.

Qualitative Analyses

As part of our mixed methods design, the qualitative data were gathered concurrently with our quantitative instruments and then explored to help contextualize our quantitative findings. Exit interview data were analyzed using a collaborative thematic analysis protocol. Using raw video data from each of the exit interviews, participant VR session logs, and text messaging, the team of researchers engaged in a collaborative, reflexive thematic analysis [50,51]. Analysis began with the extraction of excerpts that felt salient in relation to our research questions around activity in VR, emotional experience, and the effect of VR on stress. From a review of extracted excerpts, open coding was used to create a categorical code book. With the code book, researchers then revisited the data to further contextualize the categorical codes in an effort to represent the depth and breadth of experiences described by participants. This process was repeated until the research team felt we had sufficient evidence to contextualize our study findings.

Results

Participant Characteristics

A total of 118 individuals accessed the eligibility screening, 100 completed the screening, 94 were eligible, and 51 enrolled. Reasons for ineligibility included age older than 18 years (n=4), age younger than 14 years (n=1), seizure disorder (n=1), and out of the geographic area (n=1). After data collection, 7 participants were removed from those enrolled: 2 participants did not complete baseline surveys; 2 did not use the intervention (8% attrition); and although they completed all study procedures and described using the intervention, we found no headset data for 3 participants. Therefore, because we could not objectively confirm use of the headset, these participants were removed from the study. The final sample included 44 adolescents. See [Multimedia Appendix 2](#) for all participant demographic characteristics.

Participants were aged 14 years to 18 years (mean 15.82 years) and in grades 8 through 12 (mean 10.09). Participants identified their gender as boys (n=17), girls (n=23), and nonbinary or

gender fluid (n=4). Participants completed a total of 1651 (mean 45.86, SD 19.24) momentary reports of their stress level and mood during the 3-week study period. The average response rate for random, within-day reports was 33%, which was expected given the randomized schedule. In addition, participants completed 330 pre- and post-VR session logs reporting their stress and affect before and after headset use as well as their comfort level.

RQ1: How Did Teens Use RESeT and How Did They Rate Its Implementation?

Without prompting or using incentives, teens used RESeT, on average, twice a week (number of sessions: mean 6.29, SD 4.51; range 1-24) over the 21-day study period. The average duration of a VR session was 11.5 (SD 6.47; range 1-45) minutes. No significant differences were found when exploring the effect of gender, age, or depression level on VR use nor did we find that VR use affected cognitive fusion, mindfulness, or retrospective stress. We did create post hoc VR use groupings for comparison in our stress analyses. See [Table 2](#) for VR use groupings.

The average usability rating of the VR system (SUS) was good (mean 74.87, SD 11.61); 37 of the 44 participants (84%) rated the system a 68 or higher, suggesting the standalone headset was fairly easy to use without any external support. The average usability rating (IUS) of RESeT was also good (mean 76.92, SD 11.7); 35 of the 44 participants (80%) rated the intervention a 68 or higher, which suggests the VR environment was also fairly easy to use. Intervention acceptability (mean 15.67, SD 3.7), feasibility (mean 15.9, SD 2.95), and appropriateness (mean 15.23, SD 2.99) were all in the high range, suggesting participants found the RESeT content to be appropriate and acceptable. In their session logs, teens reported the environment was moderately comfortable, but reports ranged across the sample (mean 3.43, SD .992).

When asked about the future of RESeT, teens suggested that the VR environment would be most accessible and useful as a school or public library resource, allowing teens to use it on site or to check out the headset for home use when needed.

Table 2. Virtual reality use groups by gender and depression level.

| Use (number of sessions) | Gender, n (%) | | | Depression level (via PHQ-9 ^a), n (%) | | |
|--------------------------|---------------|--------------|-------------|---|----------------------|--------------------|
| | Boys (n=17) | Girls (n=23) | Other (n=4) | Mild (<5; n=13) | Moderate (5-9; n=11) | Severe (≥10; n=20) |
| Minimal (<3; n=8) | 2 (5) | 5 (11) | 1 (2) | 1 (2) | 2 (5) | 5 (11) |
| Low (3-4; n=8) | 4 (9) | 3 (7) | 1 (2) | 3 (7) | 5 (11) | 0 |
| Medium (5-7; n=15) | 6 (14) | 7 (16) | 2 (5) | 5 (11) | 1 (2) | 9 (20) |
| High (≥8; n=13) | 5 (11) | 8 (18) | 0 | 4 (9) | 3 (7) | 6 (14) |

^a PHQ-9: Patient Health Questionnaire 9.

RQ2: What Is the Experience With Using RESeT?

General Experience

In their VR Logs, teens reported a small reduction in negative affect, a slight increase in positive affect, and a significant decrease in momentary stress. See [Table 3](#) for full details.

In general, teens enjoyed their experience with the VR environment. Most reported that they liked the audio and visual design. "RESeT helps you chill out with ambient noises and being able to explore" (P1, boy, 16 years old, text message). Overall, teens who engaged in each of the activities most commonly reported liking the rock stacking activity. The least favorite activity was the painting activity.

I really liked the rock stacking. I thought that was nice because you could move the rocks and you could stack them and other places in the area...And, I was a little disappointed by the painting. [P95, nonbinary, 18 years old, exit interview]

We analyzed text message and exit interview data to understand how participants described their experience with RESeT. As a result, 4 key themes emerged: calm, regulating, forget about everything, and some discomfort. Each of these themes is described in detail in the following sections.

Table 3. Key survey outcomes over the study period.

| Survey outcomes | Baseline (n=44), mean (SD) | Postintervention (n=44), mean (SD) | 3-week follow-up (n=44), mean (SD) | F statistic (df) | P value |
|-----------------------|----------------------------|------------------------------------|------------------------------------|------------------|---------|
| Perceived stress | 19.7 (5.7) | 18.5 (4.1) | 17.4 (7.5) | 1.9 (2) | .15 |
| Cognitive fusion | 28.5 (7.5) | 26.9 (7.3) | 24.8 (9.1) | 0.4 (2) | .65 |
| Depression | 9.0 (4.8) | 5.8 (4.4) | 6.7 (5.4) | 1.0 (2) | .38 |
| Mindfulness/attention | 3.9 (0.8) | 4.2 (0.5) | 4.2 (0.8) | 1.2 (2) | .31 |

Calm

Overall, teen participants in the study felt generally positive about the environment. Teens described the environment as “calming,” “relaxing,” and “stress-relieving.” As one teen described:

Kind of makes you calm as a whole—more calm, more relaxed. [P103, boy, 17 years old, exit interview]

Another teen described the following:

I really...definitely noticed feeling a lot more calm and mindful after being in the environment and I thought it definitely has a positive impact, especially when you are depressed or anxious about something. [P80, boy, 14 years old, exit interview]

Regulating

In exit interviews, teens suggested that the VR environment helped them to regulate their moods when overwhelmed or upset. As one teen described:

Mostly I would use it when I was like really upset. And so it helped a lot there. I kind of looked forward to doing it. It changed the way I felt, like mentally and stuff. [P39, 15 years old, nonbinary, exit interview]

Some teens also described emotional regulation or making space for them to process big feelings as a result of the environment, for example:

It has 100% the ability to lower and kind of simmer any really high feelings of emotion. [P96, boy, 16 years old, exit interview]

Forget About Everything

Some teens described it more as a form of escape and distraction from unwanted thoughts or feelings, such as:

It gives teens a space to relax and calm down and just forget about everything happening in the real world. [P116, boy, 15 years old, exit interview]

Some participants mentioned feelings of escapism through the VR environment and that it was a great, but temporary, distraction from current stressors:

RESeT let us transport into another world and I forgot about the environment I was in. It transferred me to a different location. It felt like I was going on a trip so even though I had my worries in my head it felt good to forget about the physical things around me and be somewhere else. I'm going on a trip for 10-15 minutes and it relaxes me. [P71, girl, 16 years old, exit interview]

Some Discomfort

It is important to note that, for some participants, there was some discomfort with the headset causing some nausea or dizziness (n=8) or eye strain (n=3):

Well, when I first started using it, afterwards it hurt my eyes for a little bit, but then, after a while on my eyes got adjusted to it so didn't hurt anymore. [P25, girl, 14 years old, exit interview]

Nausea was typically associated with locomotion. Some described the arm swing motion as nauseating, whereas for others, teleporting induced nausea. Overall, nausea and eye strain seemed to lessen or fully resolve by adjusting the headset or getting used to using VR.

Two participants mentioned headaches as a result of using VR, particularly regarding the arm swing movement causing nausea. There was also some comparison of the environment with a video game, which may explain participants feeling bored when compared with entertainment expectations for a video game:

When I first started using the VR headset I kept on getting giant headaches and got really dizzy because I wasn't used to how VR feels yet. So at that point if I weren't doing a study I personally wouldn't continue using the headset. [P38, girl, 18 years old, text message]

RQ3: What Effect Does RESeT Use Have on the Surveyed Measurement of Retrospective Stress (PSS), Depression (PHQ-9), Cognitive Fusion (CFQ), or Mindfulness (MAAS)?

An analysis of surveyed outcomes demonstrated no significant effect of using the VR environment on retrospective stress (PSS), depression (PHQ-9), cognitive fusion (CFQ), or mindfulness (MAAS) for participants regardless of the amount

of VR use. See [Table 3](#) for details. However, we did see significant changes in momentary stress and affect, as described in the following sections.

RQ4: What Effect Does RESeT Use Have on Momentary Stress and Mood?

When exploring the pre- and post-headset session surveys, teens reported a significant reduction in negative affect, a significant

increase in positive affect, and a significant reduction in momentary stress. See [Table 4](#) for full details.

Mixed effects models of change in momentary stress over the 21-day study period found that a linear time model was a better fit than quadratic and cubic models. Stress decreased by 0.328 points per day over the study ($SE=0.12$, $P=.008$).

Table 4. Effect of virtual reality (VR) sessions on momentary affect and stress (n=44; 330 reports).

| Affect and stress | Before, mean (SD) | After, mean (SD) | Estimates (relative to “before” survey) | P value |
|-------------------|-------------------|------------------|---|---------|
| Negative affect | 9.2 (3.6) | 6.9 (2.4) | -2.3 | .001 |
| Positive affect | 10.8 (4.0) | 12.0 (4.1) | 1.3 | .001 |
| Momentary stress | 37.9 (27.1) | 24.0 (20.6) | -13.3 | .001 |

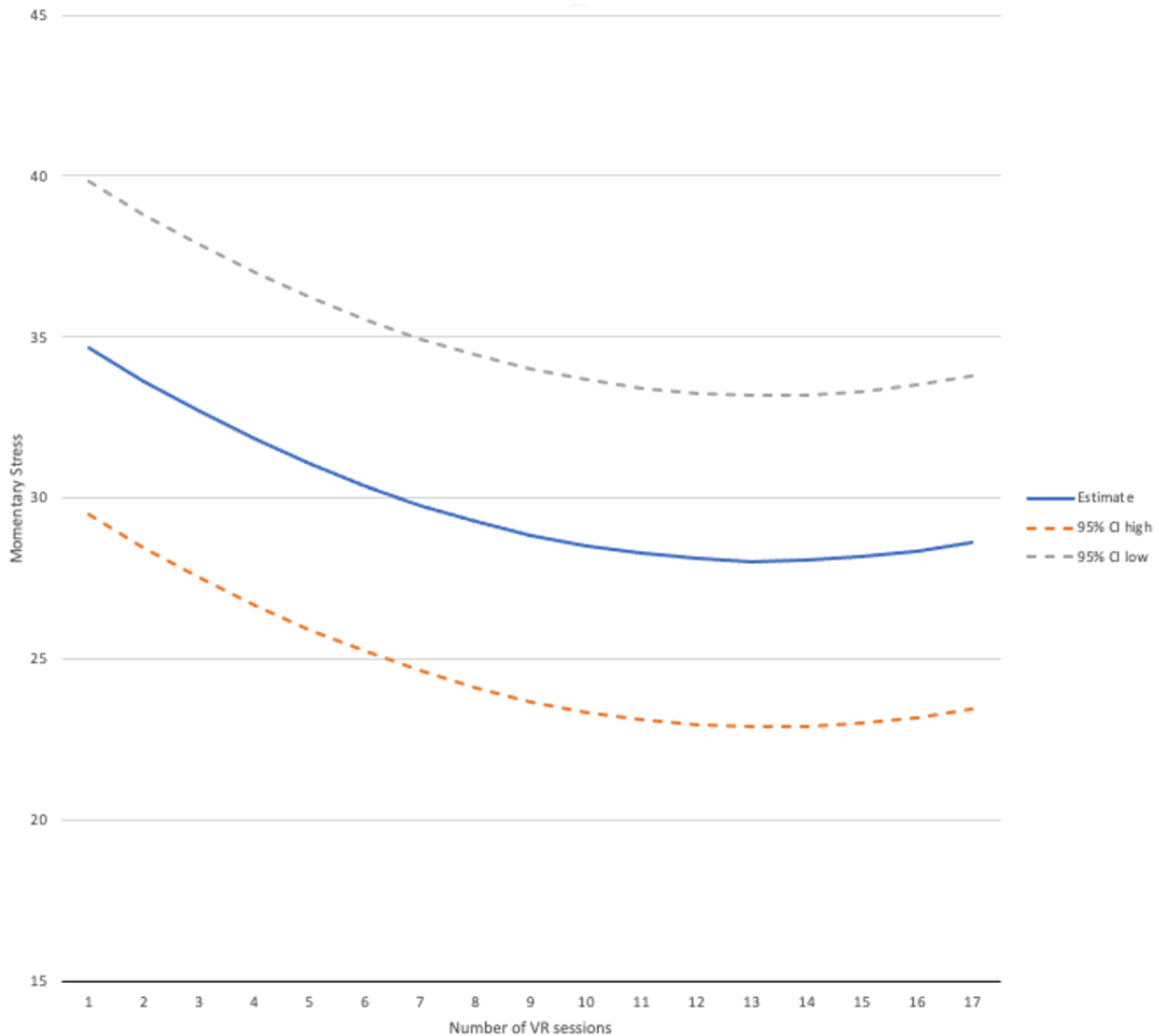
RQ4a: Do Baseline Depression, Mindfulness, and Stress Moderate Momentary Stress Over the 3-Week Intervention?

The rate of decrease in momentary stress score was not significantly moderated by baseline scores of retrospective stress (PSS: interaction=-0.021, $SE=0.021$, $P=.31$), depression (PHQ-9: interaction=-0.04, $SE=0.03$, $P=.14$), or mindfulness (MAAS: interaction=0.14, $SE=0.16$, $P=.38$).

RQ4b: Does Dosage (Frequency and Duration of VR Use) Moderate Momentary Stress Over the 3-Week Intervention?

The best-fitting mixed effects model for frequency of use included both linear and quadratic use frequency, indicating

that there was a stronger association with improved stress scores during the first several uses (linear frequency=-1.08, $SE=0.50$, $P=.03$), which decreased as frequency of use increased (quadratic frequency=0.043, $SE=0.02$, $P=.03$; see [Figure 3](#)). The best-fitting model for cumulative duration of use was linear, though the individual parameter for duration was not significant (linear minutes=0.01, $SE=0.003$, $P=.07$). A model exploring a possible interaction effect of frequency by duration on stress did not find significant effects (frequency x duration=0.001, $SE=0.001$, $P=.61$). See [Figure 3](#) for an illustration.

Figure 3. Predicted change in the stress score, with the 95% CI, by number of uses of the virtual reality (VR) headset over the 3-week period.

Discussion

Principal Findings

It was evident from this study that the VR environment was desirable and a usable system within a self-administered, autonomous home setting. In addition, teens chose to use RESeT repeatedly of their own volition despite its limited interactions. As with our previous studies [28,32], teens confirmed their desire and enjoyment of nature in VR as a stress-reducing environment.

Although RESeT did not significantly affect repeated survey measurements of depression, mindfulness, nor cognitive fusion, it did decrease momentary stress and positively affect momentary mood. This reduction in stress was correlated with the frequency of use, suggesting that self-administered VR environments may be effective to reduce momentary stress. However, the benefit from increased frequency of use tapered off with high use, suggesting that there may be a limit to the impact of RESeT over time. Counterintuitively, although frequency of use was associated with further stress reduction, duration of use was not, suggesting that longer sessions may not be more beneficial. Also likely, it could be that participants

self-regulated their use and ended a session once they felt a reduction in stress, such that long sessions and short sessions had a relatively equal impact.

Comparison With Prior Work

It was not surprising that more stable factors such as depression, cognitive fusion, and mindfulness were not significantly changed by this short-term, self-administered intervention. However, our exit interviews with teens provided strong evidence that, for some teens, the RESeT VR environment provided a place for relaxation as well as emotional regulation. Bond et al [52] found that VR allowed for “safe space to practice” interactions for adults with agoraphobia. It is feasible that VR can also provide a safe space to process big emotions for teens. Although we hoped to see significant changes in cognitive fusion given one exercise (the boat launch) was designed specifically for this purpose, teens did describe experiences of emotional regulation. Computer games have shown significant improvements in emotional regulation in adults [53], and a preliminary study found VR could both improve and measure emotional regulation in adolescents [54]. For this reason, measuring emotional regulation as a result of VR nature environment experiences may be an important factor to consider.

Previously, we conducted a 2-week study exploring a high-fidelity, commercial VR nature-based environment [19]. In the 2-week study, momentary stress was also significantly reduced, suggesting that these types of environments may be effective to reduce momentary stress. In the 2-week study, we also found participants averaged about 6 VR sessions over the study period. This suggests that, perhaps in these self-administered environments, engagement or effect may taper around 6 sessions. Interestingly, similar themes of relaxation and escape emerged from the participants' responses to the VR environment. Granted, both studies explored nature settings, but combined findings suggest teens find nature relaxing and that VR offers an opportunity to escape real-world stressors. Future design research is needed to explore further translation of evidence-based CBT, dialectical behavioral therapy, and acceptance and commitment therapy exercises into immersive VR activities in an effort to understand what types of activities are most engaging and effective.

Limitations and Next Steps

This study was an exploratory usability study of self-administered VR and therefore does not constitute a more rigorous clinical trial. In addition, this study was limited in several ways. First, to establish the effectiveness of RESeT, a control or comparison group, possibly using a well-crafted placebo VR experience, would be necessary. Second, this study was limited in the diversity of its sample (broad range of depression levels) as well as participants' self-selection and ability to self-administer the VR tool. Although each of these factors provides some real-world context about how VR may be used by teens of varying levels of depression, it also limits any generalizability of these data to other samples. Third, the study also lacks controlled data or comparison data to determine the true effect of VR on the measured variables. Fourth, the

participant-level sample size was modest and lacked statistical power to detect small to moderate effects; findings should be viewed as preliminary, consistent with the scope of an exploratory study. Finally, given the probable novelty of VR and short intervention period, teen participants likely experienced a novelty effect, and engagement may have tapered during a longer intervention period.

Further research could explore the VR headset as a community-based tool, such as in a school or library setting, to increase access for teens. VR technology has been found an engaging tool in public library settings [55], which has prompted some public libraries to launch programs to support mental health [56]. As per Kelly et al [57], we included minimal interactions, hoping not to distract participants from mindfulness. However, teens wanted more engagement and interaction; therefore, future evidence-based mental health VR interventions could explore more engaging and interactive activities, as it is likely with a larger platform, more choices, and a more diverse set of activities, teens would be more engaged with the VR platform.

Conclusion

Teens enjoyed and repeatedly used our VR environment, which included 6 evidence-based activities in an open world nature environment, without further incentive. They found the VR system and the RESeT usable, and many reported feeling relaxed or calm as a result. We found that stress decreased over time and that increased VR session frequency further decreased momentary stress. However, we also learned that increased session duration did not improve stress outcomes, suggesting that even brief VR sessions can be effective. These findings indicate that VR is a feasible and likely attractive platform for evidence-based mental health interventions.

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Data Availability

Study data are available upon request.

Authors' Contributions

EAB was the primary investigator who conceptualized the study; oversaw all study procedures, data collection, and data analyses; and led authorship of this manuscript. JS was co-principal investigator of the study; monitored all study procedures, including data collection and management; and shared senior authorship with EAB. SR and SHM helped to conduct and manage the study,

began preliminary analyses, and helped with authoring the paper. HZ and MDP conducted the analyses and authored the analysis section.

Conflicts of Interest

None declared.

Multimedia Appendix 1

RESeT VR Environment Demonstration.

[MP4 File (MP4 Video), 129744 KB - [xr_v1i1e49171_app1.mp4](#)]

Multimedia Appendix 2

Participant Demographics.

[DOCX File , 15 KB - [xr_v1i1e49171_app2.docx](#)]

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Abbreviations

- CBT:** cognitive behavioral theory
- CFQ:** Cognitive Fusion Questionnaire
- IUS:** Intervention Usability Questionnaire
- MAAS:** Mindfulness Attention and Awareness Scale
- PD:** participatory design
- PHQ-9:** Patient Health Questionnaire 9
- PSS:** Perceived Stress Scale
- REDCap:** Research Electronic Data Capture
- RESeT:** Relaxation Environment for Stress in Teens
- RQ:** research question

SG: serious game
SUS: System Usability Scale
VR: virtual reality

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Original Paper

Use of Immersive Virtual Reality in Nursing Homes for People With Dementia: Feasibility Study to Assess Cognitive, Motor, and Emotional Responses

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Abstract

Background: Physical activity interventions for people with dementia have shown promising effects in improving cognition and physical function or slowing disease-related decline. Immersive virtual reality (iVR), using head-mounted displays, facilitates realistic experiences by blurring the boundaries between VR and the real world. The use of iVR for people with dementia offers the potential to increase active time and improve dementia therapy and care through exercise interventions. However, the feasibility of using VR use in people with dementia, considering changes in motor, cognitive, psychological, and physiological parameters, remains insufficiently investigated.

Objective: This study aims to investigate the feasibility of using iVR in people with dementia or mild cognitive impairment in nursing homes. Specifically, we examined changes in motor performance (balance and mobility), cognitive performance (global cognition and executive functions), emotional responses, and fear of falling using iVR.

Methods: Utilizing a pre-post design, this study recruited 35 participants with mild-to-moderate dementia, assessed by the Mini-Mental State Examination (MMSE). Participants underwent a single session involving iVR exposure, with pre- and postexposure assessments and a feedback form, to exclude negative effects on cognitive and motor functions, mood, anxiety levels, and balance performance. The use of iVR involved 4 scenes, with a total length of 8 minutes. These scenes depicted a park with short and rather passive impressions presented as a 360° video in a head-mounted display. Before and after using the iVR, cognitive parameters were assessed using the Trail-Making Test A (TMT-A), motor parameters were assessed using the FICSIT-4 (Frailty and Injuries: Cooperative Studies of Intervention Techniques-4) and Timed-Up-and-Go (TUG) tests, and psychological parameters were assessed using the Dementia Mood Picture Test, State-Trait Anxiety Inventory, and Short Falls Efficacy Scale-International (Short FES-I). The Emotion Rating Scale and the duration of use were recorded during use, and a feedback questionnaire was completed afterward in addition to the posttests. Paired *t* tests and Wilcoxon tests were used to examine pre-post differences.

Results: Of the 35 initial participants, 33 completed the study, which corresponds to a dropout rate of 6%. All 33 participants, who had a mean of 83.71 (SD 5.01) years, had dementia. They showed no statistically significant difference in cognitive and motor performance before and after iVR use. Thus, no negative effects on cognitive and motor functions, mood, anxiety levels, and balance performance were observed. The emotion rating scale also showed that 72% (n=24) felt joy and fun during iVR use, 100% (n=33) showed no emotions such as fear, sadness, or anger, and 93% (n=31) were attentive during iVR use.

Conclusions: The feasibility of using iVR for people with dementia can be rated positively. There were no changes in motor, cognitive, or emotional parameters that would increase the risk of falls or other negative emotional reactions during or after iVR

use. Further studies are needed to investigate prolonged use in a more stimulating computer-generated environment and possible physical and cognitive tasks for people with dementia in nursing homes.

Trial Registration: German Clinical Trials Register DRKS00030616; <https://drks.de/search/de/trial/DRKS00030616>

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KEYWORDS

persons with dementia; virtual reality; VR; immersive virtual reality; iVR; head-mounted display; HMD; physical performance; physical activity; physical function; motor performance; Alzheimer's disease; Alzheimer's; Alzheimer's treatment; Alzheimer's care; Alzheimer's symptom control; dementia; dementia therapy; dementia care; cognitive decline; cognitive impairment; cognitive impairments; neurocognition; neurology; neurologist; neurologists; nursing home; nursing homes; nursing facility; senior home; long-term care center; long-term care facility

Introduction

The number of people with dementia is expected to increase to over 152 million worldwide by 2050 [1], representing a high societal burden in terms of costs and care [2]. Dementia treatment is predominantly based on symptom reduction, with drug therapy often being associated with negative side effects [3], making treatment with nonpharmacological interventions important [4]. In particular, physical activity interventions have shown promising effects in improving cognition and physical function or slowing disease-related decline among people with dementia [5-9]. Additionally, quality of life and the ability to perform activities of daily living can also be positively affected by physical activity [7,10,11]. With the increasing use and dissemination of digital health applications in the past, there are new opportunities to complement or improve dementia care (ie, to respond to the individual needs of people with dementia) [12]. Virtual reality (VR) is a possibility that has great potential for treating cognitive impairment in the nursing home setting.

VR is based on computer simulations that allow individuals to enter an artificial environment. A distinction is made between nonimmersive, semi-immersive, and immersive VR technologies. Nonimmersive methods are based on desktop systems, with stereoscopic displays and head tracking, while semi-immersive methods are based on large single-screen or tabletop displays [13]. Immersive VR (iVR) technologies refer to the specification of the hardware (eg, the field of view, screen resolution, and refresh rate), as well as the degree of interaction and how isolated the user is from the outside world [14]. Clay et al [15] define iVR as “systems that encompass the user's field of view and where virtual motion replicates actual head or body motion.” For this purpose, head-mounted displays (HMDs) are usually used to create an even better 3D perspective to completely block out the real environment. Consequently, the immersive method leads to the most authentic experiences [16] and is therefore of particular interest.

VR has already been used in studies to improve cognitive function in both healthy individuals [17] and those with cognitive impairment [18] and to promote well-being in people with dementia [19]. The conclusion of a systematic review and meta-analysis review on the effects of VR-based task-oriented training on people with dementia or mild cognitive impairment (MCI) is that VR interventions are promising nonpharmacological approaches for improving cognitive and motor function [20]. Despite promising intervention effects

[21-23], the feasibility of VR technologies in dementia therapy and care has not yet been sufficiently investigated [18]. Only a few studies with small sample sizes have examined the feasibility of VR in people with dementia [24]. In particular, direct changes in motor, cognitive, psychological, and physiological parameters, which are particularly important for the safety of people with dementia in everyday nursing home life, have scarcely been investigated following the use of VR technologies. In this context, it is important to take a closer look at cybersickness, which could increase the risk of falling after the use of VR technologies and is associated with injuries requiring hospitalization [25] and a decrease in activity, mobility, and quality of life [26]. Similarly, for an iVR intervention to be sustainable in nursing homes, there should be no deterioration in motor performance, confusion, and anxiety after iVR use. The feasibility of iVR in terms of safe use in people with dementia regarding influencing motor, cognitive, or emotional factors is currently inconclusive [27,28].

Therefore, the primary aim of this study is to investigate the feasibility of using iVR in people with dementia or MCI in nursing homes from a safety perspective. The focus of this study is to investigate any adverse effects of iVR on motor and cognitive function and general well-being. In particular, this study examines motor performance (including balance and mobility), cognitive performance (such as global cognition and executive function), emotional responses, and fear of falling before and after the single iVR use. This study can be seen as a preliminary step in assessing the suitability of iVR for physical training in people with dementia in nursing homes.

Methods

Ethical Considerations

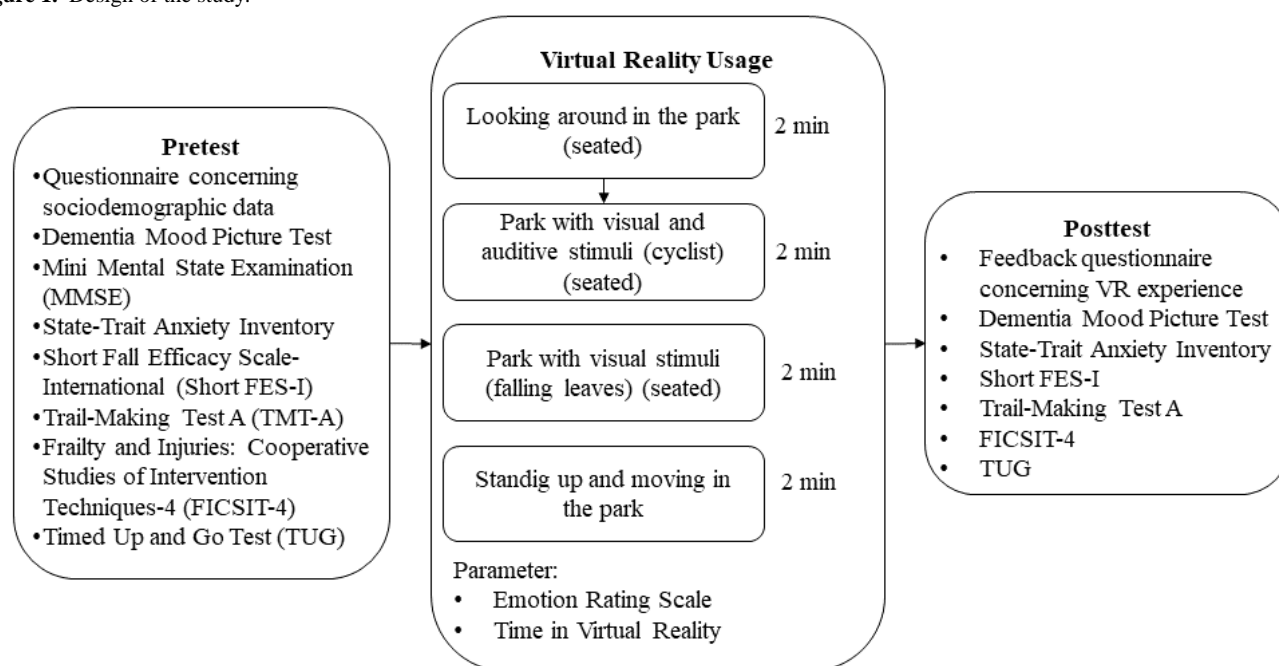
The research protocol followed the Declaration of Helsinki and ethical approval was granted by the Ethics Committee of the Otto-von-Guericke University Magdeburg (number 131/22) and the Karlsruhe Institute of Technology. The study was registered in the German Clinical Trials Register (DRKS00030616). The participants and their legal guardians provided written informed consent after being briefed on the study's details. Data were collected from December 2022 to July 2023. Participants were not offered any incentives/compensation for participation.

Study Design and Sample

The study was designed as a pre-post study to examine possible side effects of iVR by comparing motor and cognitive functions and emotional responses before and after iVR use (see Figure 1). All measurements were carried out in a single session lasting approximately 45 minutes. In each of the 2 cities, Magdeburg and Karlsruhe, 3 facilities were contacted to identify potential participants with the help of nursing home staff. The following inclusion criteria were applied: age over 70 years, MCI or mild to moderate dementia based on the Mini-Mental State Examination (MMSE [29]), no untreated hearing or visual

impairment, and self-sufficiency in standing and walking unaided or with a rollator. Exclusion criteria included hypertension, severe cardiovascular disease, and significant motor impairment. To check the inclusion criteria, a questionnaire on the sociodemographic data was completed together with the participants' legal guardians before the start of the study. Initially, 35 participants were included in the study, 23 (66%) in Magdeburg and 12 (34%) in Karlsruhe. Prior to the baseline assessments, the participants and their legal guardians were informed about the aims of the study, and written informed consent was obtained from the participants' legal guardians.

Figure 1. Design of the study.



Test Battery

To test the feasibility of iVR in people with dementia and its impact on motor performance, cognitive performance, and emotional response, the participants underwent several tests before and after the iVR application (Figure 1). The tests assessed the participants' mood using the Dementia Mood Picture Test [30], state and trait anxiety using the State-Trait Anxiety Inventory [31], fear of falling using the Short Falls Efficacy Scale-International (Short FES-I) [32], attention using the Trail-Making Test A (TMT-A) [33], balance performance using the FICSIT-4 (Frailty and Injuries: Cooperative Studies of Intervention Techniques-4) scale [34], and mobility using the Timed-Up-and-Go test (TUG) [35]. During the iVR use, the Emotion Rating Scale and another questionnaire adapted from Appel et al [27] (Multimedia Appendix 1) were applied. Additionally, after removing the HMD, participants completed a feedback questionnaire about their experience and general interest in VR.

In the Dementia Mood Picture Test, the participants are presented with 6 emoticons expressing different moods (negative mood, positive mood, cheerfulness, concern, sadness, and anger). Participants are asked to choose the emoticon that best describes their current mood. Cheerful is considered the best,

followed by a positive mood. In the State-Trait Anxiety Inventory, participants are asked to rate their general and current emotional state. A score is calculated based on the answers given, with higher scores being associated with higher levels of anxiety (state and trait max. 80 points [31]). The Short FES-I asks participants about their fear of falling in various situations. The score is also calculated based on the answers given, and again, with higher scores associated with a greater fear of falling (maximum 28 points [32]). To complete the TMT-A, the participants enter numbers 1 to 25 (jumbled together on a paper) in ascending order. The time taken and the number of errors made are recorded, with a shorter time and fewer errors associated with better attention. The FICSIT-4 tests 4 successive levels of static balance (bilateral stance, semitandem stance, tandem stance, and unilateral stance), each performed with eyes open and closed. Points are awarded according to the duration of each level (maximum 10 seconds). These points are summed up to give a total score (maximum 28 points), with higher scores associated with better static balance performance [34]. For the TUG test, participants are asked to stand up from a chair, walk 3 meters, turn 180°, walk back to the chair, and sit down again. The time taken to complete this task is measured, with a shorter time associated with a lower risk of falling [35].

The Emotion Rating Scale was scored by a test instructor during iVR use by observing participants' facial expressions. The emotional expressions (happiness, anger, fear, sadness, and general attention) and their duration (never, less than 16 seconds, 16 to 59 seconds, 1 to 5 minutes, and over 5 minutes) were documented.

The feedback questionnaire (Multimedia Appendix 1), which was administered after the iVR use, consisted of 17 questions (eg, "Did you like the VR?"), which were scored from one to five points, with more points indicating a higher level of agreement. The answers to negative questions (eg, "Did you feel nauseous while watching the VR?") were inverted. The questions were divided into 3 dimensions: "Response to VR" (questions 2, 6, 7, 10, 11, 15, 16), "Feedback to VR" (questions 1, 3, 4, 5, 8, 9), and "Comfort" (questions 12, 13, 14, and 17). The points were later summed up to dimension scores and a total score (maximum 85 points).

Virtual Reality Setup

During the iVR use, the participants sat on a chair between 2 SteamVR Base Stations (version 2.0; HTC Corp), which tracked the position of the HMD (Figure 2). The Pimax Vision 5k super (Pimax Inc) (170° horizontal FOV, 2560 x 1440 pixels per eye, 90 Hz refresh rate) was wired to a computer via cable and presented the virtual environments, which consisted of different scenes provided as 360° videos recorded in the Geschwister-Scholl-Park in Magdeburg, using the GoPro Hero 8 (GoPro Inc) (Figure 2). These videos were projected onto the inner surface of a virtual sphere (radius of 50 m) modeled with Blender (version 3.2; Blender Foundation). The virtual environments were then constructed using Unity (Unity Technologies). Self-written C# scripts were used to enable dynamic scene control within iVR, by allowing seamless scene transitions and pauses with simple button presses on a standard keyboard used by the test instructors. SteamVR (version 1.25.1; Valve Corp) was used to transfer the scenes from Unity to the HMD.

Figure 2. Virtual reality setup. Chair between 2 SteamVR Base Stations 2.0 with Pimax Vision 5k super (top). Participant with head-mounted display (HMD) and virtual park environment (bottom).



Procedure

After the pretest, the iVR use began, consisting of 4 scenes, each showing the same specific section of a park presented as a 360° video for 2 minutes. First, the HMD was demonstrated to the participants and placed on their heads. Once they were comfortable, the first scene began, showing the park without any additional elements (see Figure 3). During the first scene, the participants were asked to look around and describe the environment. The second scene showed a cyclist riding through the same section of the park, signaling their presence by ringing

a bell. In the third scene, the participants saw leaves falling to the ground, controlled by the instructor pressing the space bar on the computer keyboard. The final scene was identical to the first, but the participants were asked to stand up and walk a few steps if they wished and if the instructors and nursing staff felt it was feasible. While standing, the participants were always secured by at least 2 instructors. The scenes were presented directly, one after the other, without a break. After the last scene, the HMD was removed from the participants' heads, and the feedback questionnaire was administered. The posttest was then completed to detect deviations from the baseline measurement.

Figure 3. Immersive virtual reality (iVR) park environment (top, mid) with cyclist (bottom).



Statistical Analysis

Statistical data analysis was performed using SPSS (version 28.0; IBM Corp). The pre- and posttests (State-Trait Anxiety Inventory, Short FES-I, TMT-A, FICSIT-4, and TUG) were compared using paired t tests. If the prerequisites for a t test were unmet, the Wilcoxon test was used instead. The significance level was set at $\alpha=.05$. To avoid the cumulation of alpha errors, the significance level was adjusted using the Bonferroni-Holm correction. Cohen classification was used to interpret the effect sizes ($d=0.2/r=0.1$, small; $d=0.5/r=0.3$, moderate; $d=0.8/r=0.5$, large). The Dementia Mood Picture Test, MMSE, Emotion Rating Scale, and feedback questionnaire were analyzed descriptively.

Results

Sample characteristics

Two participants dropped out during the study, corresponding to a dropout rate of 6%. The first participant signaled disinterest at the beginning of the measurement day and dropped out immediately, while the other participant was bothered by the HMD and wanted to take it off. Thus, 33 (94%) of the 35 people with dementia (mean age 83.71, SD 5.01 years) were analyzed in the study. Table 1 shows the sample characteristics.

Care was taken to ensure that participants with dementia had no untreated visual or hearing impairments. The HMD could also be used with visual and/or hearing aids.

Table 1. Sample characteristics.

| Characteristics | Sample (N=33) |
|---|---------------|
| Age (years), mean (SD) | 83.71 (5.01) |
| MMSE ^a score, mean (SD) | 21.2 (4.2) |
| Sex, n (%) | |
| Male | 7 (21.2) |
| Female | 26 (78.8) |
| Experience with VR ^b ; n (%) | 6 (18.2) |
| Degree of dementia n (%) | |
| No dementia | 1 (3) |
| Mild dementia | 21 (63.6) |
| Moderate dementia | 11 (33.3) |

^aMMSE: Mini-Mental State Examination.

^bVR: virtual reality.

Outcome Parameters

Feasibility

Observations of the participants during the iVR use revealed that 72% (n=24) felt pleasure and fun, as measured by the Emotion Rating Scale. Additionally, all 33 (100%) participants showed no fear, sadness, or anger during the iVR use, and 31 (93%) out of 33 patients were attentive and able to respond to everything in the environment and thus interact with the iVR (Figure 4).

The feedback form according to Appel et al [27] showed that the participants rated the iVR as positive on average. The total score was 73.21 (SD 7.1) out of a possible 85 points. This is

also reflected in the individual dimension of the questionnaire, as outlined in the Methods section. The participants responded very positively to the iVR use. On average, the participants rated this dimension 31.2 out of 35 points. The participants also gave positive feedback on the iVR, by rating this dimension with 24.9 out of 30 points. The final dimension, comfort, was rated positively with 17 out of 20 points (see Figure 5). The questions of the dimensions can be found in Multimedia Appendix 1. Additionally, the actual time spent in iVR was recorded showing an average of 389 seconds (6.5 seconds minimum; the maximum was 480 seconds or 8 minutes). The first 3 scenes (Figure 1) were completed without issue; some participants did not want to try scene 4 (standing up).

Figure 4. Results of the Emotion Rating Scale.

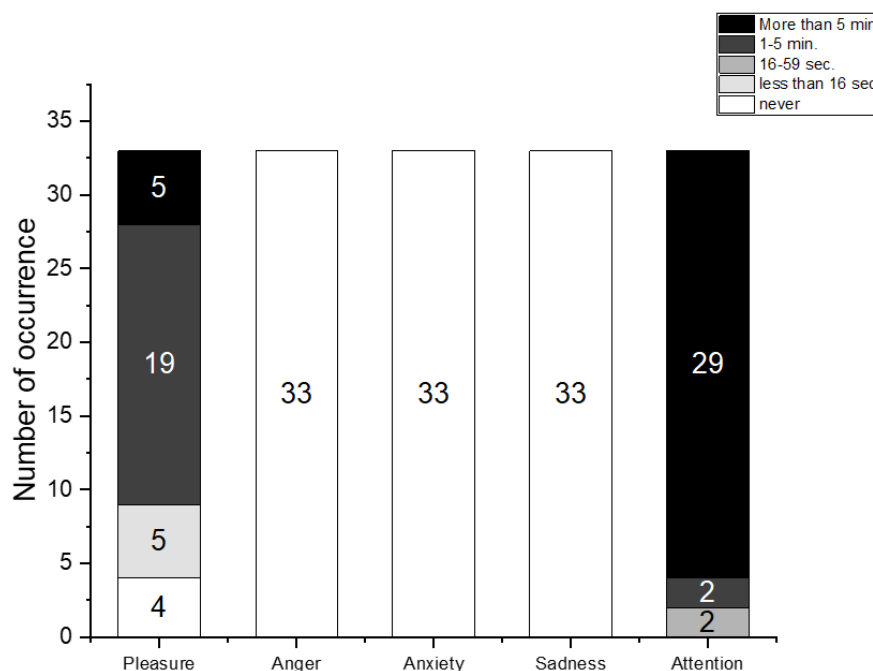
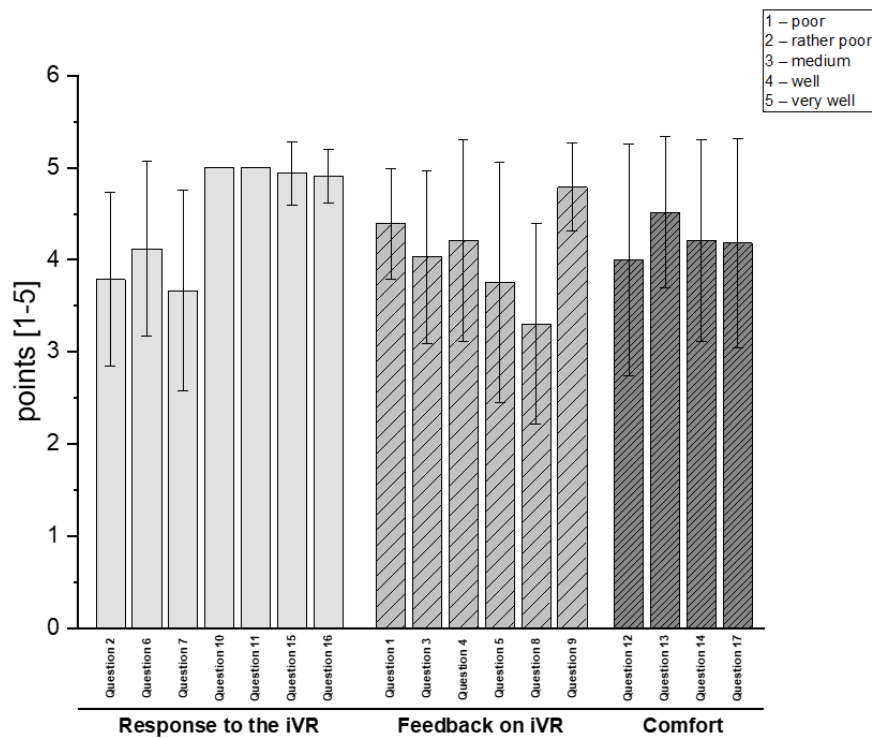


Figure 5. Results of the protocol response after immersive virtual reality (iVR) use.

Motor and Cognitive Performance and Mental State

The results show no significant changes in cognitive and motor performance and mental state after iVR (Table 2) (TMT-A: $t_{26}=1.244$, correct $P>.99$; state anxiety: $t_{32}=1.653$, correct $P=.65$; trait anxiety: $t_{32}=1.754$, correct $P=.53$; FICSIT-4: $t_{29}=-2.531$, correct $P=.16$; TUG: $t_{28}=-0.036$, correct $P>.99$; short FES-I: $z=-1.461$, correct $P=.68$). However, almost all parameters showed slight but not statistically significant improvement after iVR use. On the TMT-A, people with dementia improved by a

mean of 9.5 seconds. State anxiety and trait anxiety improved by 2.65 and 3.39 points, respectively. The FICSIT-4 showed an increase of 1.44 points from pre- to posttest. The results of the TUG and the short FES-I did not change.

The Dementia Mood Picture Test also reflects a slight improvement: 27 (82%) out of 33 participants were in a good mood before iVR, and 6 (18%) were cheerful. After iVR, the distribution of the 2 moods was balanced so that 16 (49%) out of 33 participants were in a good mood and 17 (51%) were in a cheerful mood.

Table 2. Results of the pre- and posttest.

| Outcomes | Pretest, mean (SD) (95% CI) | posttest, mean (SD) (95% CI) | <i>P</i> value (Bonferroni-Holm) | Effect size (<i>d</i>) |
|--|--------------------------------|---------------------------------|----------------------------------|--------------------------|
| Parametric tests (<i>t</i> test) | | | | |
| TMT-A ^a (n=27) | 118.43 (70.10) (90.67-146.20) | 108.91 (80.60) (77.01-140.8) | .225 (>.999) | 0.24 |
| State anxiety (points) (n=33) | 33.94 (8.36) (29.42-36.46) | 31.29 (10.25) (26.31-34.28) | .108 (.648) | 0.28 |
| Trait anxiety (points) (n=33) | 33.45 (8.69) (28.87-36.07) | 30.06 (10.51) (25.14-33.21) | .089 (.534) | 0.30 |
| FICSIT-4 ^b (points); n=30 | 15.63 (5) (13.76-17.51) | 17.07 (5.10) (15.16-18.98) | .026 (.156) | 0.43 |
| TUG ^c (n=29) | 15.53 (5.60) (13.41-17.65) | 15.56 (5.50) (13.47-17.65) | .976 (>.999) | 0.007 |
| Nonparametric tests (Wilcoxon test) | | | | |
| Short FES-I ^d (points) (n=33) | 7.50 ^a (7.00-11.25) | 7.00 ^a (7.00-10.00) | .114 (.684) | 0.25 ^e |

^aTMT-A: Trail-Making Test A.

^bFICSIT-4: Frailty and Injuries: Cooperative Studies of Intervention Techniques-4.

^cTUG: Timed-Up-and-Go.

^dFES-I: Falls Efficacy Scale-International.

^e Median and 25th/75th percentile, Correlation coefficient *r*.

Discussion

Principal Findings and Comparison to Prior Work

This study demonstrates the feasibility of using iVR in people with dementia without significant changes or effects on emotional, cognitive, or physical outcomes. Thus, no negative side effects were observed following iVR use. Out of 35 participants, only 2 dropped out during the study, and only 1 of these was due to the participant feeling disturbed by the HMD. Thus, the dropout rate for iVR use was low, which is comparable to Appel et al [27], who observed iVR use in people with cognitive and/or physical impairments and Thapa et al [22] who analyzed iVR use in people with MCI. Liao et al [23] reported a higher dropout rate (8 out of 42) in people with MCI due to low motivation during the iVR use, but this was a 12-week intervention. Other studies using VR in people with dementia did not report dropout rates, so no further comparisons are available [36,37].

In general, it might have been expected that people with dementia would have challenges participating in the iVR [38]. On the one hand, there is a lack of haptic feedback, and on the other, there is acoustic information from the real world (eg, instructors speaking and birds singing in the iVR at the same time). The feasibility of using iVR can be positively rated by the average time participants used the iVR, which was 6.5 minutes (out of a maximum of 8 minutes). Additionally, the reasons for discontinuing iVR use, which were more due to the low-stimulus environment rather than excessive demands or overstimulation, also indicate good feasibility. The first 3 scenes of iVR use could be followed by all participants without any issues.

Most of the participants (n=31, 93%) were attentive during the iVR experience, which has not been reported previously. As far as we know, Mendez et al [36] only found that the participants' talkativeness increased while wearing an outdated HMD that did not allow full immersion. Pleasant feelings such as joy or fun were observed in the majority of participants, particularly in 5 (15%) participants over a longer period (>5 min). This is a positive observation, and it echoes the study by Appel et al [27], where VR exposure was generally considered to be enjoyable. In addition to the positive emotional reactions, the question arises as to whether confusion, which occurs disproportionately often in people with dementia [39], is related to the use of VR. Confusion or challenging behavior may be associated with extreme or extremely negative emotions [40], which we sought to observe during the iVR use. In our study, no participant showed anxiety, sadness, or anger during iVR use. Thus, our findings agree with those of Appel et al [27] and Mendez et al [36] regarding negative emotions.

The emotional observations are particularly important for future long-term use in an iVR intervention, as a sustainable intervention in nursing homes should only be implemented if additional benefits in the real world are observed. The joy and attention experienced, combined with the absence of fear, anger, and sadness, suggest a positive impact on the quality of life. Regarding challenging behavior among people with dementia in nursing homes and home care [41], future studies could also investigate whether positive outcomes can be achieved through iVR use.

Since people with dementia are known to face challenges in correctly identifying and associating negative emotions [42], the questions about the iVR use were particularly relevant and

helpful in correctly classifying the observations. Our results show that participants generally rated the iVR use as positive, as assessed by the feedback questionnaire based on Appel et al [27]. The responses to the questions are summarized under the 3 dimensions of response, feedback, and comfort.

The general response to the iVR use was assessed by questionnaire items such as, “This helped you to relax and free yourself from unwanted feelings or thoughts,” “You felt like you were panicking when you saw this,” or “Did you get dizzy while watching VR?” All questions about dizziness or nausea, as well as confusion or disorientation, were answered in the negative, so no negative effects are to be expected. Similar results were also reported by Appel et al [27], who found that 92% of respondents did not experience nausea while using VR and that other side effects such as dizziness, disorientation, or confusion were not detected. The general response to the use of iVR can therefore be considered positive, which was also shown in the feedback subdimension. Questionnaire items were asked regarding this realm, such as, “The virtual world appeared to be very real to you,” “This was fascinating to observe,” or “You want to spend more time viewing this environment.”

Questions about the comfort of the HMD included whether participants were able to get used to the HMD, whether they found the HMD heavy, and whether they were able to move their heads well. High scores were found for these items, so the comfort of the HMD can be rated as very good. This was also reported by Appel et al [27], where 88% of the participants negated the question, “Did the VR HMD feel too heavy?” In general, however, this assessment must be qualified in the sense that the participants in our study only used the HMD for a relatively short period of time and did not perform any guided movements with it.

There were no statistically significant changes in motor and cognitive performance or mental state after the single use of iVR. Side effects from iVR use can therefore be ruled out. This is a particularly positive finding for people with dementia, as it could be expected that negative effects such as dizziness or nausea may occur after just a few minutes of using iVR [38]. The nonsignificant improvements in almost all tests and questionnaires after iVR use suggest a learning effect due to the short time interval between measurements. Assumptions that the improvements are also due to an improvement in mood, as has been found in people with depression [43], are speculative and need to be investigated in further studies. To assess the changes, it is important that physical and cognitive performance does not decline significantly after the use of iVR, as this would lead to an increased risk of falls and thus more intensive care.

State anxiety and trait anxiety also improved and may also be related to positive emotions. The more positive emotions were reflected in a change in the Dementia Mood Picture Test, which showed better mood scores after iVR use, along with cheerful feelings, which may be related to a more positive mood. While the results for mobility and fear of falling remained the same, there were changes in balance after iVR use. This has not been previously reported and cannot be explained presently. The mean differences in the FICSIT-4 test meet the threshold of the minimal clinically important difference [44], but the results are

not statistically significant and can therefore only be interpreted as trends. This may indicate a possible effect of longer-term interventions, which needs to be verified in future studies. In addition to the findings on balance, mobility, and fear of falling, we observed that some participants did not want to try to stand up with the HMD iVR system. This suggests that some participants may have felt unsafe while using iVR, which needs to be considered for future iVR interventions, especially those involving increased physical activation.

Strengths and Limitations

The strength of this study is the use of iVR for people with dementia under real conditions in nursing homes. To date, there have been few studies of this nature, and we were able to show that the use of iVR in nursing homes is feasible and is not expected to have a negative impact on people with dementia.

As with any study, there are several limitations. The first is the rather low-stimulation VR environment, where there was no direct activation in the form of physical activity. The rationale was to investigate the general feasibility and gain experiences with iVR for people with dementia to assess and possibly minimize the risks of such VR uses. This was particularly necessary for this target group to gain a first impression and can therefore be seen as a preliminary step in assessing the suitability of iVR for physical activity in people with dementia in nursing homes. We aimed to avoid situations that could lead to cognitive disorientation, emotional reactions, or physical responses such as dizziness. The second limitation is the relatively small sample size, which, although considered appropriate for the study design and objectives, does not allow for generalization. Additionally, the sample had a rather mild degree of dementia, which limits the generalizability to the whole population of people with dementia. The third limitation is the single use of iVR in a predominantly seated position. The single use of iVR and the predominantly seated position influenced the interaction and incentive to be physically active, at the same time legitimizing and strengthening the use of iVR to promote physical activity. Therefore, the duration of the intervention, the sample included, and a critical review of the cost-benefit ratio need to be included in future studies.

Future Directions

Future studies should build on these findings by including more stimulating environments that encourage more physical activity. Such environments could potentially increase engagement and movement to exercise, overcoming the limitations of this study's low-stimulation VR environment. To this end, the feasibility of computer-generated virtual environments for people with dementia should be examined, as they provide a higher degree of individualization and interaction compared to 360° videos. Additionally, longer-term iVR interventions with multiple sessions should be investigated to assess lasting effects on motor and cognitive performance. Future research should also investigate the potential of iVR to positively impact the quality of life of people with dementia by examining its effects on mood, emotional well-being, and general engagement. Finally, the economic feasibility of implementing iVR interventions needs to be considered. Future studies should include cost-benefit analyses to determine the overall value and

feasibility of iVR as a regular intervention in care settings. By addressing these areas, future research can further elucidate the potential of iVR to improve the well-being of people with dementia and contribute to the development of effective and scalable interventions.

Conclusion

The changes observed in our study due to the use of iVR do not indicate that the use of iVR increases the risk of falling or causes adverse effects such as dizziness or nausea. Therefore, we can

conclude that iVR use can be applied in nursing homes for people with dementia or MCI and that no debilitating emotional, cognitive, or physical changes are to be expected afterward. However, care must be taken during iVR use to ensure that there are no events that increase the risk of falling. In this study, which involved a single use of iVR in a predominantly seated position and a relatively low stimulus iVR environment, there were no complications. Further studies are needed to investigate prolonged use with a more stimulating environment and possible physical and cognitive tasks in people with dementia.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Assessment battery.

[DOCX File, 24 KB - [xr_v1i1e54724_app1.docx](#)]

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Abbreviations

FICSIT-4: Frailty and Injuries: Cooperative Studies of Intervention Techniques-4

HMD: head-mounted display

iVR: immersive virtual reality

MCI: mild cognitive impairment

MMSE: Mini-Mental State Examination

Short FES-I: Short Falls Efficacy Scale-International

TMT-A: Trail-Making Test A

TUG: Timed-Up-and-Go Test

VR: virtual reality

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Enhancing Mixed Reality Simulation Training Technology With Real-Time Performance Visualization: Mixed Methods Study With Medical First Responders

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Abstract

Background: Mixed reality (MR) simulation training is emerging in paramedical education as a way to practice responding to stress-intensive scenarios like mass casualty incidents in a safe and controlled environment. Current training platforms, however, lack real-time stress and human performance monitoring tools.

Objective: The study aims to enhance MR training for medical first responders through real-time evaluation of performance and stress levels, leveraging biosignal monitoring and advanced analytics to allow instructors to tailor feedback and maintain optimal challenge and safety levels.

Methods: The study includes a structured, multiphase approach including initial requirement gathering (structured interviews and cocreation workshops), an online design survey, iterative prototype development, and a field trial (including training observations and interviews). Data were collected from 5 end user consortium members across Europe. Quantitative data from checklists were analyzed using frequencies and percentages to understand feature usage and event occurrences. Qualitative data from semistructured interviews and cocreation workshops were transcribed, coded, and subjected to thematic analysis to identify patterns and insights into the usability and effectiveness of the enhanced features in the MR training.

Results: The study identified a number of requirements that medical first responders have for an MR training system, including requirements not included in currently available solutions. A total of 80 performance metrics were initially identified and refined to a set of 54 metrics, which were categorized into key performance indicator groups such as scene safety, triage performance, and communication. Requirements for smart wearables to monitor stress levels are provided and highlight the importance of a user-centered design process to provide users with effective tools that fit their needs. Stress visualization preferences are described in the form of a dashboard as well as in virtual environments surrounding the avatar. Using an iterative design process and user feedback, a training system was developed, integrating real-time performance tracking and stress monitoring. The field trial provided insights into the practical use of these features during a real training exercise, showed interaction preferences between trainer and trainees, and highlighted further improvement opportunities.

Conclusions: This research enhances MR training for paramedics by integrating real-time performance metrics and stress indicators based on a human-centered design approach that aligns with end user needs, thereby laying the foundation for developing more effective and immersive training solutions for high-stress professions.

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KEYWORDS

mixed reality; immersive technologies; simulation training; simulation; paramedic; medical first responders; human performance; stress; stress monitoring; human-centered design

Introduction

Background

Medical first responders (MFRs) play a critical role in saving lives and providing emergency care in challenging and stressful

situations. The number of mass casualty incidents (MCIs) has significantly increased in recent years [1]. However, providing effective training for MFRs can be a difficult task due to the complexity and unpredictability of emergency scenarios. Training methods for first responders are still analog, with

minimal presence of digital and immersive technologies. For instance, the majority of training continues to adhere to conventional exposition-style instruction based on theories and examples presented in books and presentations [2]. This type of training can improve learning but primarily targets cognitive memory rather than physical/muscle memory [3]. Since the majority of training and operations in the first responder industry adhere to repetitive instructional designs and protocols, physical memory is considered to be of utmost significance [4].

Extended reality (XR) simulation training provides the opportunity to train a multitude of scenarios that capture all training possibilities found within mass casualty or natural disaster events without the extensive resources needed for real-life simulation training [5]. MFRs are offered new training methods based on learning management systems and XR training as a result of recent advancements in the field of immersive technologies. Due to the service's portability and accessibility, XR learning management systems have been found to improve student retention and engagement [6].

With an increased interest in XR simulation training, which includes virtual reality (VR), augmented reality, and mixed reality (MR) [7], the need emerges for novel training interfaces that offer real-time feedback and support for both trainees and instructors. The possibility to digitalize and automatically track training performance metrics as well as psychophysiological metrics such as stress and cognitive workload bring considerable advantages in terms of training quality as well as efficiency. However, incorporating these key performance indicators (KPIs) into XR training platforms remains a relatively unexplored field in MFR training.

Objectives

This study aims to enhance MR training solutions for MFRs by addressing the specific needs of end users and incorporating their iterative feedback throughout the development process. By integrating real-time performance evaluation and stress level monitoring through advanced KPIs and biosignal analysis, this research seeks to optimize training outcomes. The objective is to enable instructors to deliver feedback based on objective data, ensuring a balanced approach that maximizes both the challenge and safety of the training experience. Through these innovations, the study aims to fill existing gaps in MR training, ultimately improving preparedness and response effectiveness in emergency scenarios.

The research addressed the following research questions:

Research question 1. What are the key performance metrics in MR training that enable trainers to effectively engage with and mentor MFR trainees?

Research question 2. How can stress level indicators be integrated into an MR training platform tailored for MFRs?

Related Work

The application of XR technologies in emergency response training has gained substantial interest in recent years [8-11]. These technologies offer a safe and controlled environment for rehearsing emergency scenarios without the associated risks [12,13]. Studies have demonstrated that XR training can achieve

performance outcomes on par with, if not superior to, traditional training methods, making it a practical solution for complex simulations like MCIs and triage [14-16]. Unlike traditional large-scale exercises, which are resource-intensive and logistically demanding, XR training has been shown to be more cost-effective, though the initial investment in hardware and software remains a consideration [17,18].

Although XR has the potential to transform health care training [19], the research on its application for MFRs in MCIs is still in its early stages, revealing both promising results and notable limitations. Positive findings indicate that XR simulations provide an immersive and engaging experience [20], with participants reporting a heightened sense of presence and increased confidence in their abilities [21]. Studies comparing XR training to live simulations have found comparable efficacy in knowledge acquisition, decision-making skills, and user satisfaction, with no significant difference in the accuracy of triage decisions between paramedic students trained using XR and those who underwent live simulations [14,22]. Furthermore, XR offers a cost-effective and safe environment for learning, enabling repeated practice without real-world consequences [17,23].

Despite these benefits, a critical gap in the literature is the integration of real-time performance monitoring within MR training environments. Current studies primarily focus on the immersive qualities of MR and its ability to mimic real-world scenarios, often neglecting the necessity for immediate performance feedback. Effective training requires accurate and prompt evaluation of trainees' actions, essential for ensuring that the skills acquired in virtual environments transfer effectively to real-world emergencies. Kirkpatrick's model [24] suggests that evaluating training effectiveness comprehensively requires assessing reaction, learning, behavior, and results. Identifying specific, measurable, action-oriented, relevant, and timely KPIs is crucial [25,26]. Baetzner et al [27] found that most MFR training studies rely on an overall performance score, task completion time, and decision accuracy as external measures. However, self-reported metrics dominate these studies, underscoring the need for more objective evaluation methods since traditional measures are prone to different biases [28]. As training designs evolve and incorporate new technologies like XR, it is critical to maintain rigorous evaluation methodologies to ensure the transfer of training to real-world applications [29]. Digitalization of measurements in VR solutions presents an exciting opportunity to integrate more nuanced and continuous evaluation metrics, which can further enhance the effectiveness of MFR training [30].

Given the high-pressure nature of MCIs, it is imperative to incorporate the assessment of cognitive factors such as stress in simulation training. Evaluating these factors provides a holistic understanding of a trainee's capacity to perform under stress, ensuring that they are not only technically proficient but also mentally resilient when faced with real-world emergencies [31]. Previous studies showed that high stress levels can impair cognitive functions crucial for decision-making [32,33]. Simulation-based MR training enables practical application within environments that mimic the perceptual, motor, and cognitive demands of high-stress situations [34,35].

Real-time measurement of stress in training environments presents unique challenges that differ significantly from traditional posttraining subjective evaluations. Although posttraining assessments often rely on self-reported data, real-time stress assessment requires the integration of physiological monitoring tools that can capture immediate responses to stressors, offering a more objective view of trainees' stress levels [36,37]. Currently, biosignals such as heart rate (HR), heart rate variability (HRV), electrodermal activity (EDA), blood pressure, respiratory rate, and electroencephalography are commonly used for stress measurement [38].

However, incorporating these biosignal measurements into real-world training environments poses significant challenges. Most research to date has been conducted in controlled lab settings where participants' movements are limited, minimizing noise in the data [39]. In contrast, training environments that involve high levels of physical activity introduce additional difficulties, as movement can introduce noise and artifacts into biosignal recordings.

Despite the potential of these physiological markers, achieving accuracy and reliability in real-time stress measurements, especially in dynamic training environments, remains a complex task [40]. The challenge lies in the need for sensors that can reliably track these biosignals during movement-intensive scenarios and the development of algorithms capable of processing and interpreting data in real time without introducing latency.

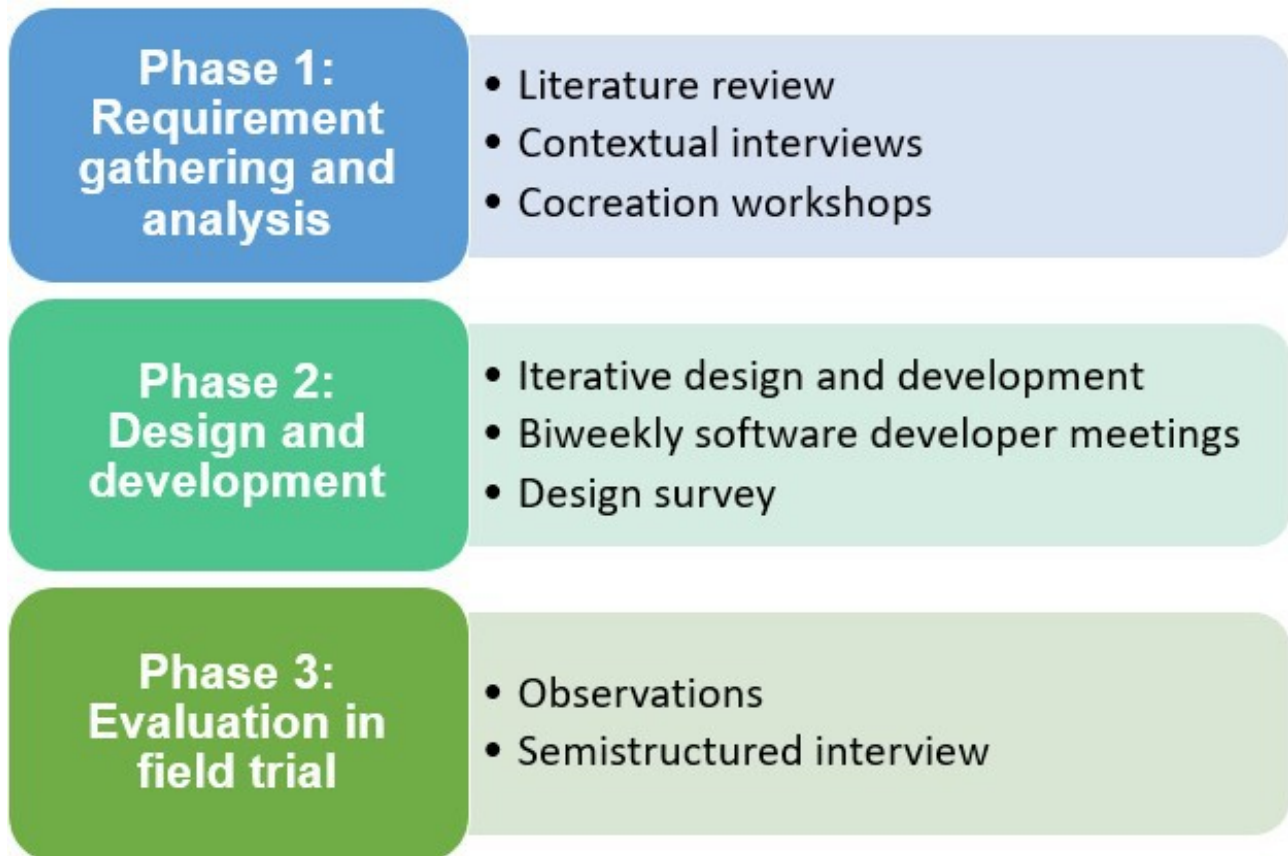
The visualization of physiological signals (ie, HR, HRV, and breathing rate) is a key component in biofeedback applications

designed to help individuals understand and manage their own stress levels [41]. Research on biosignal visualization has shown that presenting physiological data in an accessible, user-friendly format can enhance self-awareness, allowing individuals to recognize stress responses and use strategies to mitigate them [42]. However, limited research can be found about visualizing stress data for third-party observers, such as trainers or supervisors, in a way that is informative and actionable. Research on the visualization of physiological data in XR is limited as well and mainly involves investigating its influence on social factors, such as social connections [43]. Further research is needed to develop more sophisticated visualization tools that can convey essential information quickly and discreetly, enhancing the utility of real-time stress monitoring in training contexts.

Methods

Overview

All studies described in this manuscript are part of the Horizon 2020 project MED1stMR [44]. The goal of the research project was to design an MR simulation training system for MFRs that is based on the needs and preferences of end users. This study focused specifically on enhancing immersive training environments to improve performance and stress measurement, as these were identified as critical areas of concern by the consortium members. The methodology included a structured multiphased research structure with a strong focus on human-centered design methods. The research protocol included a phase for requirements gathering, as well as iterative design and development and evaluation, as shown in [Figure 1](#).

Figure 1. Research protocol: 3 phases and methods.

Recruitment

MFRs and trainers (also referred to as end users) were recruited from the following consortium members to participate in the studies: Servicio Madrileño de Salud, Hellenic Rescue Team, Johanniter Österreich Ausbildung und Forschung Gemeinnützige GmbH, Region Jämtland Härjedalen, University Hospital Heidelberg, and Campus Vesta, as well as external partner Sanitätspolizei Bern.

For the contextual interviews and cocreation workshops, participants were recruited via email and word of mouth between October and December 2021. The online survey was distributed in January 2023, with each organization sending an invitation link and a brief description of the study to their MFRs.

For the field trial, participants were recruited through Johanniter Österreich Ausbildung und Forschung Gemeinnützige GmbH from April to June 2023, using email and word of mouth as the primary recruitment methods.

Requirements Gathering and Analysis

For the collection of end user requirements, contextual interviews were held with 30 participants (16 female, 14 male) and 41 MFRs (19 female, 22 male) who contributed to cocreation workshops (the interview guide was developed with MFRs and research experts from the consortium and can be found in [Multimedia Appendix 1](#)). The goal of the cocreation workshops was to engage end users in the process of scenario design and collect input regarding training goals and features. Workshops included traditional and immersive prototyping as

Nguyen et al described in a separate study comparing the 2 techniques [45].

As part of the structured interviews, participants were asked to list the KPIs their organization is using to assess trainees in real-life MCI training, including assessment methods, rating scale (eg, categorical, numerical, checklist), and time of assessment (during training or debriefing). Upon completion of the interviews, all KPIs, along with descriptions, were compiled into an Excel sheet ([Multimedia Appendix 2](#)) and categorized by assessment type (eg, safety-related aspects, triage performance, application of triage algorithms, treatment of patients, use of equipment, and communication and coordination). The MoSCoW method [46] was used to prioritize KPIs. This method rates each item as must have (Mo), should have (S), could have (C), or will not have (W). The single point of contact for each end user organization coordinated with their team to complete the ratings. In the next step, the technical development team added information about feasibility and resource requirements for each item in the list to get a better understanding about the scope.

To receive input regarding the stress level indicator specifications, participants were asked about their preferences regarding biosignal recording wearables (eg, chest strap, smartwatches, sticky electrodes on the chest) and biosignals to use for stress classification (eg, electrocardiogram [ECG], EDA).

Design and Development

In the design phase, an agile development process [47] was used to develop the MR system, including the scenario editor; 2

scenarios; stressors; avatar appearance and wounds; virtual medical tools; performance monitoring; and debriefing tools. The initial requirements collected in phase 1 were transferred to the product backlog and development was divided into manageable, incremental builds, allowing for regular assessment and adaptation. Biweekly software developer meetings were held to foster close collaboration between developers and end users, ensuring that the evolving needs and feedback of trainers and trainees were continually integrated into the development process.

The technical development team was unclear about how the stress level indicator should be visualized and what level of information should be included; therefore, an online survey was conducted via the survey platform LimeSurvey. Mock-ups were created based on best practice (eg, stress indicator of smartwatches) and examples from the literature [48,49] and presented to end users as still images in an online survey (Multimedia Appendix 3). The survey took about 10 minutes to complete and was distributed through the end user organizations of the project. In total, 54 MFR trainers from 8 different MFR organizations across 7 European countries participated.

Evaluation in Field Trial

Overview

Finally, a field trial was conducted to gather feedback from end users and observe their interaction with the newly developed features. In total, 36 MFRs (6 female, 28 male) and 4 trainers (1 female, 3 male) participated in the field trial.

The MR training setup encompasses a 10 × 10 training field, allows for teams of up to 4 trainees, and is equipped with a head-mounted display and trackers placed on the trainees' hands, feet, and back. To ensure seamless communication, trainees and trainers are provided with headphones, which also facilitate role-playing interactions with dispatchers. The training environment is further enriched with 2 patient simulator manikins [50], which offer a tangible patient interaction experience. Additionally, a biosignal collection device [51] is integrated into the system, capturing real-time ECG and EDA sensor data to monitor trainee physiological responses. The current stress level indicator utilizes a combination of HR and HRV to categorize stress into low, medium, and high levels. This approach is adapted from a previous research project about VR training for law enforcement, as described by Zechner et al [52].

After being introduced to the study and signing the informed consent form, participants filled out a demographic questionnaire and received an introduction to the MR system and the task, which involved performing first triage at 2 different MCI sites (1 scenario each). The training was conducted in teams of 4 with 1 trainer, who also voice-acted the emergency dispatcher and included the following scenarios that were conducted in random order.

Scenario 1

Emergency teams in 2 ambulances (2 trainees each) respond to a bus-car collision on a highway with multiple casualties. They

arrive at the virtual scene after hearing the emergency call from the dispatcher and receive updates about the accident's specifics such as weather conditions and potential hazards, including a stray dog and a damaged light pole. The trainees' tasks involve patient assessment, risk management, and clear communication. The exercise concludes with a detailed situation report to the triage commander.

Scenario 2

In a tunnel-based MR training scenario, emergency medical teams from 2 ambulances respond to a multivehicle accident caused by a public transport bus colliding with a car that had a tire explosion. The accident involves at least 3 cars and the bus, with around 15 passengers. As the scenario unfolds, trainees face additional challenges, including locating a missing child and managing potential risks from a gasoline-powered and damaged bus. The exercise concludes with a detailed situation report to the triage commander.

During 7 training sessions, observations took place, including checklists for usage of features, reports on predefined events, time stamps, and open notes, which were later organized into themes. On the fourth day of the field trial, all 4 trainers participated in a semistructured interview (Multimedia Appendix 1).

Statistical Analysis

For training observations, both quantitative and qualitative analysis were used to analyze data from training observations. Checklists were analyzed by calculating frequencies and percentages for each feature usage and event occurrence to understand their prevalence. Trainer-trainee interactions were recorded through note-taking and later analyzed by identifying and highlighting significant statements or behaviors and these were grouped into themes.

Interview data were transcribed and subjected to thematic analysis [53]. Codes were assigned to significant statements, which were then grouped into themes to identify common patterns and insights regarding the usability and effectiveness of the MR training system. The thematic analysis of qualitative data was conducted using Atlas.ti.

Ethical Considerations

All studies within the Med1stMR project were approved by the Karl Ruprecht University of Heidelberg (Antrag AZ Beu 2023 1/1, August 15, 2023).

Results

Phase 1: End User Requirements

End users expect the technology in MR training to be user-friendly and cost-effective, while improving training outcomes and safety. They desire a system that is intuitive to use and operates smoothly to foster broad acceptance within their organization. They also anticipate that the technology will be more cost-effective than traditional MCI simulation training in the long run. MR training is expected to enhance training outcomes by accommodating more participants, improving the efficiency of training time, enhancing the quality of debriefing

with detailed and objective information, and offering the opportunity for trainees to assume different roles in repeated simulations.

Workshop participants identified key aspects of MCI training, including scene safety assessment; internal and external communication; coordination; first and second triage; trauma assessment and treatment; prioritizing for transport; and both prehospital and in-hospital MCI management. Participants underscored the importance of enhancing the quantity and quality of training with regard to scene safety assessment; communication and coordination; and triage procedures, which are currently lacking in MCI training. Triage training often relies on paper patients or role-players, both offering limited realism. Paper patients (paper cards that list a patient's injuries and vital signs) reduce the complexity of the triaging process. Role-players, despite being able to simulate a victim's status using make-up and behavioral cues, are inherently limited in representing patient symptoms. MR simulations allow MFRs to develop a deeper understanding of MCI procedures, thus improving preparedness and response efficacy.

Regarding KPIs, during the end user requirement collection phase, we gathered 80 performance metrics, of which 57 were prioritized as high and 56 were selected for live tracking. After consolidation of items that were similar enough, a total of 54 performance metrics (42 high priority and 36 marked for live tracking) remained. With the aim to reduce this number to a realistic and implementable workload, all metrics were categorized into the following KPI groups: 3S (scene, safety, situation); triage performance; patient assessment and treatment; use of equipment; communication and coordination; and team performance.

Trainers emphasized that monitoring KPIs in real time would help them better understand a trainee's progress and areas of improvement. In a dynamic training environment, capturing metrics such as response time, decision accuracy, status of the patient simulation manikin, and task completion rate can reveal valuable insights about a trainee's aptitude and readiness for real-world scenarios. Real-time performance monitoring can also facilitate immediate feedback, a process that can significantly enhance the learning progress by highlighting areas of strength and those needing improvement promptly after or even during training sessions.

However, not all performance metrics are equally important in every scenario but rather depend on the specific training objective. To cover a variety of training goals and scenarios, a library feature has been requested for the MR training platform, allowing trainers to select up to 8 KPIs for real-time monitoring.

Furthermore, it has been highlighted that monitoring team performance metrics such as task distribution, communication efficiency, and collaborative decision-making can offer a comprehensive understanding of team dynamics and synergy, in addition to individual KPIs [54].

Furthermore, the workshops with end users underscored a pivotal shift from merely focusing on physical safety to a more holistic approach that encompasses psychological well-being. Although MR training reduces physical risks compared to

real-life simulations, the heightened realism and immersive nature can increase trainee stress. Instructors should be able to monitor trainees' stress levels, ideally based on biosignals, throughout the training exercise.

End users also pointed out the need to identify specific stressors for MCI scenarios. These stressors can range from environmental factors (like poor visibility) to operational challenges (such as resource shortages). One notable stressor is the condition of the victims in the scenario. Their health status, both physical and mental, can impact trainee stress. Therefore, it is essential to detail the victims' health trajectory throughout the training, including key physiological parameters during critical stages.

The visualization of stress levels was a frequently discussed topic by end users, who considered stress level monitoring as a must-have feature of the platform but were concerned about the feature distracting the instructors from their already-high task load. Showing trainees their own and colleagues' stress level was dismissed early in the project because it would not resemble a real MCI and this was viewed as critical for privacy reasons.

The following requirements were identified:

- **Visibility:** Stress levels should be visible only to trainers to maintain trainees' immersion.
- **Accessibility:** Stress levels should be continuously visible to trainers without active involvement (eg, mouse clicks).
- **Association:** It should be easy to link the stress visualization to the respective trainee's avatar.
- **Interpretability:** The visualization should be straightforward, avoiding complex numerical displays.
- **Distraction:** The design should ensure the visualization is noticeable but not distracting.

These insights from the workshops provided valuable guidance for designing MR MCI training that is both effective and mindful of trainee well-being. Following the guidance of experienced trainers, stress level visualization options were designed and tested with end users through an online survey, as reported in the next section.

Phase 2: Design and Development

Overview

The design and development phase was the core phase of this research project and lasted for 14 months. During this time, prototype tryouts had been organized for end users to test the current version of the system, monthly consortium meetings were held to discuss the current status and gather feedback, and biweekly software developer meetings took place online.

KPI implementation was discussed in software developer meetings, leading to further refinement of KPI requirements. Not all KPIs were available in real time, either because they required manual input from trainers or because data transfer and processing could only be done offline. Initial usability testing of the basic prototype, conducted during the design and development phase, revealed that users found it very difficult to monitor more than 10 KPIs simultaneously during training sessions. This finding informed the design adjustments made

to ensure the interface remained manageable and focused for trainers during real-time training. From the 54 performance metrics identified by end users, a subset (Table 1) was prioritized for real-time tracking and display, aiding trainers in effectively steering the training sessions.

Real-time stress level monitoring was enabled by wearables and biosignal sensors (Figure 2). After evaluating various

wearables and biosignal sensors, end users preferred a chest belt or sticky electrodes, both of which were integrated into the system for further testing (Table 2). Participants suggested useful biodata sources for real-time stress measurement, including HR, breathing rate, brain activity, and galvanic skin response. However, they expressed a preference for following state-of-the-art methods, acknowledging their lack of expertise in this field.

Table . Summary of key performance indicators mapped to training goals.

| Metric | Description | Training goal |
|--|---|---|
| Overall timing of scenario | Time taken by trainees to make medical decisions and provide an incident overview | Organize and coordinate work at mass casualty incident efficiently |
| 3S (scene, safety, situation) assessment | Evaluation of scene, safety, and situation; identifying and mitigating environmental risks and hazards | Evaluate and manage the safety and security of the scene |
| Trainee stress levels | Monitoring the stress levels of trainees during the training to adjust challenge levels | Effective decision-making capabilities in highly stressful situations |
| Communication skills | Assessing the clarity and precision of communication among trainees | Effective team coordination and information exchange in emergencies |
| Patient assessment | Evaluating the trainees' ability to assess patients using the Airway, Breathing, Circulation, Disability, Exposure (ABCDE) approach | Accurate and timely patient care and prioritization |
| Time taken to triage | Time spent by trainees on triaging each patient | Identifying delays in patient assessment and intervention |
| Medical task accuracy | Accuracy of medical procedures performed (eg, correct application of a tourniquet) | Performing medical tasks correctly and efficiently |

Figure 2. MED1stMR system description. MR: mixed reality; VR: virtual reality.

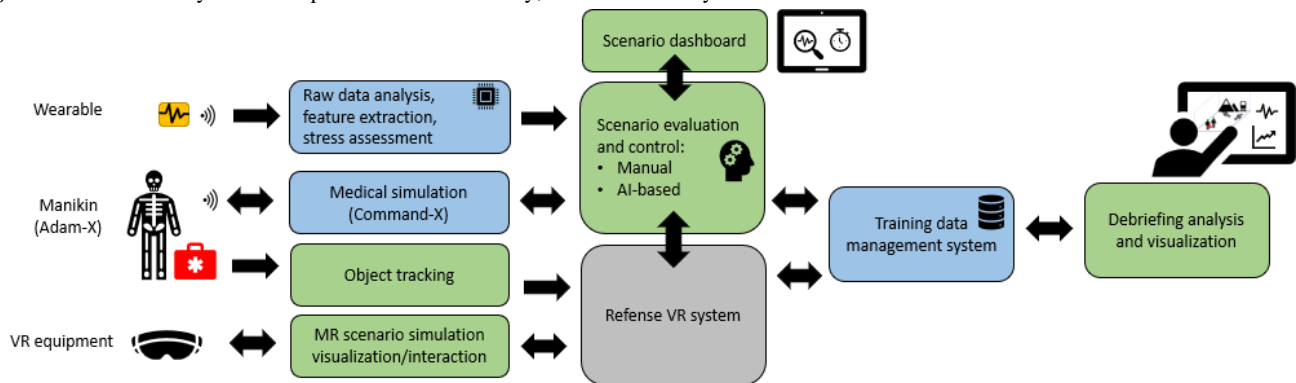


Table . Summary of requirements for the smart wearables.

| Features and needs | Notes |
|---|---|
| Free movement and disturbance-free | |
| Wearables should not impede the trainee’s ability to do their job | This requirement is different between the training goals of the training modules “first arriving ambulance,” first triage, and second triage |
| Wearables should not be “felt” (eg, tightening of a blood pressure cuff) | To allow immersion in the simulation world and not distract trainees |
| Wearable form | |
| Form follows function. Potential wearable forms include a wristband, watch, suit, vest, or shirt. | The participants were open to various forms that the smart wearable could take, whichever would make it easiest to measure the needed biodata streams |
| Not too many wearables (ideally 1 integrated wearable) | The trainees do not want to wear ≥ 4 wearables |
| Measurement | |
| Stress level | Stress was noted as the most important measure |
| Situational awareness | Situational awareness was mentioned as a “nice-to-have” measurement |

Design Preferences of Stress Level Indicator (Online Survey)

Results of the design survey clarified visualization preferences of end users and helped technical development teams implement the various visualizations.

Respondents provided feedback on five different real-time stress level indicators in the VR view (Figure 3): (1) circle, (2) aura, (3) belt, (4) battery, and (5) triangle, which were displayed in random order.

The highest overall preference was indicated for the circle, ranked as most preferred by 12 participants (55%), followed by the triangle with 4 participants (18%), icon and aura with 3

participants each (14%), and no participants indicated the belt as the most preferred option.

For the side panel (Figure 4), we wanted to know what color scheme trainers preferred to indicate trainee’s current stress levels. The traffic light scheme was considered more appropriate (22 participants, 65%) than the heat map style (12 participants, 35%). Regarding the graph type, the majority of participants found horizontal bars easy to read and interpret (18 participants, 55%) compared to a gauge type (16 participants, 48%) and vertical bars (10 participants, 30%).

Based on the survey results, a stress visualization interface was created (Figure 4).

Figure 3. Five examples of real-time stress visualizations presented to end users. A: circle; B: aura; C: belt; D: battery; E: triangle.



Figure 4. Trainer view of the mixed reality interface (left: view of the virtual environment; right: real-time performance monitoring).



Phase 3: Evaluation in Field Trial

During the field trial, training observations of 7 training sessions took place. Each session consisted of 4 trainees who went through an introductory scenario to get familiar with the MR system, followed by 2 training scenarios and a debriefing. On the last day of the field trial, semistructured interviews were conducted with 4 trainers to gather insights on the real-time performance metrics and their utility during MR training (Figure 5).

During the training sessions, our observations revealed a consistent utilization pattern of performance evaluation features by trainers. All trainers routinely accessed the feature that allowed them to verify which triage card was assigned to each patient and if it matched with the recommended card. This feature was particularly popular toward the end of the scenario, ensuring that all patients had been triaged appropriately.

Although minor corrections were occasionally given to trainees between scenarios, comprehensive performance feedback was reserved for the posttraining debriefing sessions. This approach emphasized the importance of performance metrics during debriefings rather than real-time interactions during training. However, the recorded real-time tracking of KPIs was consistently used in every debriefing session. Spanning approximately 20 minutes, these sessions highlighted the KPI tracking feature as an invaluable tool, a sentiment echoed by the trainees.

Each trainer had conducted at least 3 training sessions before the semistructured posttraining interviews.

Trainers identified the following as the most crucial real-time performance metrics in MR training:

- Overall timing of scenario: all medical decisions should be made within 10 minutes (depending on the number of casualties) and trainees should be able to give the dispatcher an overview of how many red, yellow, green, and black patients are at the incident site
- 3S (scene, safety, situation) assessment (ie, identify, communicate, and reduce any potential environmental risks or hazards)
- Trainee stress levels (allows trainers to intervene if trainees appear not challenged enough)
- Communication (clear and precise)
- Patient assessment and triage decision (Airway, Breathing, Circulation, Disability, Exposure approach to assess and treat the patient)
- Time taken to triage (aids in intervention if trainees spend excessive time on a single patient)
- Medical task accuracy (eg, application of a tourniquet)

Although trainers emphasized limiting the instructions given during simulation training, they acknowledged the automated tracking's value. It provided a rapid overview of the number of patients triaged, the accuracy of triage, and the specific trainee responsible. The "time to triage" metric was particularly beneficial, enabling trainers to prompt trainees (eg, by requesting a status update via dispatcher radio) when they took too long.

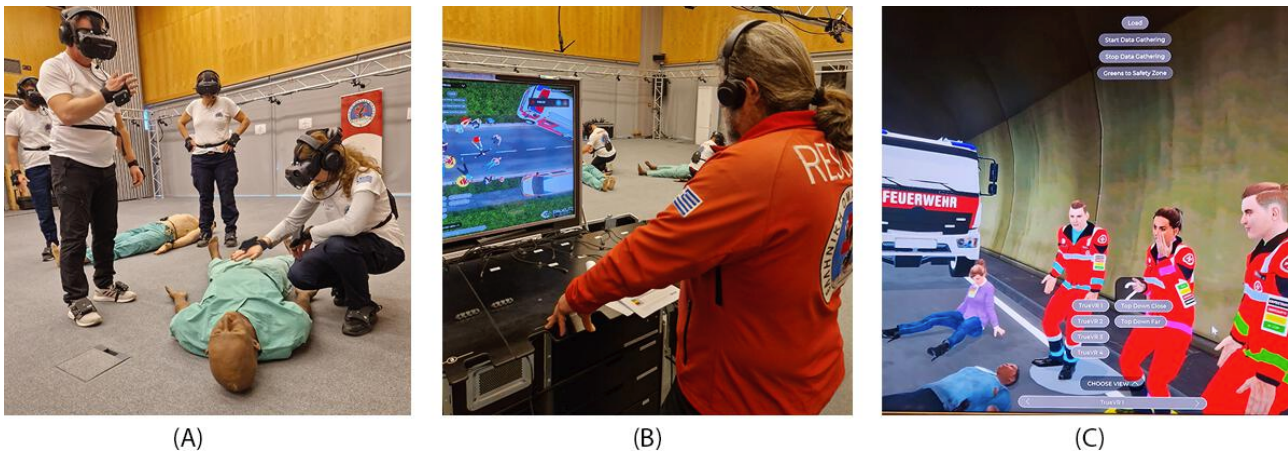
All trainers reported frequently consulting the circle under the avatar to check trainees' stress levels and claimed to have had a good overview at all times throughout the training.

For subsequent updates, trainers expressed a desire for enhanced interactivity options to modulate trainee stress levels. This could be achieved through (1) patient simulators and nonplayer characters with adjustable parameters like pulse and breath rate or (2) the ability to introduce audiovisual stress cues ad hoc. Furthermore, more time in the tutorial scenario was requested,

to give trainees the chance to test all features at least once and get familiar with the virtual environment and how to interact with patient avatars. They reported that it was sometimes not

clear if a trainee struggled because of the MR technology or their skills and knowledge, which is relevant when evaluating their performance.

Figure 5. MED1stMR field trial to evaluate features of the mixed reality training platform. A: patient simulator manikin; B: trainer station; C: tunnel scenario in VR view. VR: virtual reality.



Discussion

Principal Findings

This research aims to enhance MR training for MFRs by addressing key research questions. First, we identified crucial performance metrics, such as scene safety assessment, communication efficiency, triage accuracy, and patient management, which enabled trainers to effectively engage with and mentor MFR trainees. Second, we integrated a stress level indicator into the MR training platform using real-time biosignal analysis, allowing trainers to monitor trainees' current stress levels during the training session.

Incorporating a performance monitoring tool emerged as a high-priority request from MFR organizations during the requirement collection phase. The integration of KPIs into MR training provides a structured and measurable approach to evaluating trainee performance and supports trainers in the debriefing process. End users consider this a significant advancement over traditional methods, which often lack objective performance metrics. Literature [27,54] suggests that the inclusion of real-time performance indicators can significantly enhance learning outcomes by providing immediate feedback and enabling targeted interventions. Our study extends this knowledge by demonstrating the practical application of KPIs in MR training, with trainers identifying key metrics such as overall timing, 3S assessment, and communication skills as crucial for effective training. Although most KPIs appeared highly important during the requirements collection phase, field trials led to a refined focus on actionable and timekeeper metrics for display in real time. Other KPIs were deemed more suitable for posttraining debriefings. This shift in priorities underscores the evolving understanding of KPI relevance as trainers gain hands-on experience with the MR platform. Although MR technology offers a seemingly rich array of tracking possibilities, the key lies in selecting and translating the most impactful KPIs to ensure effective engagement and mentoring of MFR trainees.

Both trainers and trainees appreciated features incorporated into the virtual environment that provided immediate feedback, such as the cessation of bleeding only when a tourniquet is correctly applied. Such immediate feedback mechanisms enhance the training experience by providing real-time validation or correction while fostering a more immersive and instructive environment.

The capability to repeat scenarios multiple times in MR training has been highlighted as a significant advantage over traditional real-world simulation training because it allows trainees to refine their skills through practice [55]. Enhancing MR training platforms with real-time performance monitoring further empowers trainers with the ability to adjust scenarios on the fly based on the actual performance of trainees. This dynamic adaptability ensures that training sessions are not only more efficient but also personalized to meet the unique needs and skill levels of individual trainees. Real-time monitoring provides trainers with immediate insights into trainees' performance, enabling them to tailor scenarios to challenge and develop specific competencies.

The inclusion of stress level monitoring in our MR training platform addresses a critical gap in traditional MCI training methods, which often overlook the psychological well-being of trainees. Previous research has highlighted the impact of stress on decision-making and performance in emergency scenarios [34]. A stress level indicator can be seamlessly integrated into the MR training platform by using biosignals for real-time monitoring through wearable sensors, such as chest belts, sticky electrodes, or watches [41]. The stress level indicator should be visible only to trainers, continuously accessible without active interaction, easily associated with trainees' avatars, straightforward to interpret, and designed to be noticeable without being distracting. The preferred indicator, as per user feedback, is a simple and easy-to-interpret visual element, like a circle attached to the trainee's avatar with 3 stress level thresholds (low=green, medium=yellow, high=red).

Displaying real-time stress levels was regarded as a highly valuable and innovative feature of MR simulation training. For trainers, it enables quicker identification of whether a trainee is overwhelmed or underengaged, allowing for immediate intervention, thus maximizing the efficiency of training time. For trainees, this ensures their safety and psychological well-being, while also fostering optimal training environments that are conducive to effective learning and skill development.

In this research, a relatively simple stress model was used [52], calculating a combination of HR and HRV and categorizing the results into 3 groups: low, medium, and high. Our focus was on visualization and interface integration, as this was a major concern of our end users and the current literature showed a noticeable gap regarding the detailed exploration of these aspects. However, more comprehensive and robust models for stress assessment are documented in existing research [38,56]. These models often adopt a multimodal approach, incorporating measurements like ECG-related features and EDA [36].

Regarding stress level visualization, while no specific research was found on techniques for conveying stress levels to third-party observers (eg, trainers) in MR, our approach drew inspiration from biofeedback [57], biosignal visualization methods [58], and social biofeedback systems outside the MR domain [43].

Strengths and Limitations

A key strength of this research lies in its user-centered design process and the evaluation of MR training in real-life training settings. Engaging end users and trainers throughout the project allowed us to tailor the system to the specific needs and challenges faced by MFRs. By conducting field trials and workshops with professionals from various European countries, the study provided actionable insights into how MR training can enhance skill development. Additionally, the iterative feedback from trainers was instrumental in refining performance metrics and the user interface, ensuring the training system's practicality and relevance to real-world scenarios.

However, this research also has several limitations. First, there may be a selection bias since the end users and trainers involved were volunteers rather than randomly selected participants. Although we attempted to mitigate this by recruiting a diverse group from multiple European countries, the sample may still not fully represent the broader population of MFRs. This limitation may influence the generalizability of our findings. Future research should consider a randomized participant selection process to improve representativeness and enhance the validity of the results.

Second, the relatively small sample size of trainers and trainees in the field trial limits the generalizability of the findings. Although the study provided valuable insights, the experiences observed may not reflect those of a larger, more diverse group of MFRs. To address this limitation, future studies should aim to include a larger sample size, which would offer more robust and widely applicable insights.

Third, integrating MR training into existing curricula requires further investigation to understand how this technology can be effectively adopted within current emergency response

frameworks. Although this study focused on developing and refining the MR training system, future research should explore best practices for curriculum integration and acceptance within emergency response training programs.

Last, the current assumption that including performance metrics and stress level monitoring in MR training will improve learning outcomes and transfer to real-world MCIs is mainly based on existing literature and the experiences of trainers and subject matter experts. This could have influenced the study's approach and conclusions. To evaluate the sustained impact of these interventions, a longitudinal study is recommended. Tracking trainees over time would provide a more comprehensive understanding of the long-term benefits and applicability of MR training in real-world situations.

Despite these limitations, the study lays a solid foundation for future research by providing initial insights into the effectiveness of MR training for MFRs and identifying areas for further development.

Future Directions

Future studies should address these limitations by including a more diverse participant pool, a larger sample size of trainers, and a comprehensive evaluation of curriculum integration strategies. Restricted by the limited resources of this research project, only a small selection of KPI analysis and display was automated; in future work, more sophisticated and automated methods for tracking and evaluating KPIs should be investigated. This includes the development of digital checklists and enhanced data integration systems to facilitate continuous training progress and provide trainers with more robust tools for assessment.

ML algorithms have the potential to significantly improve data processing and pattern recognition in this context. Supervised learning models, such as linear regression, decision trees, and support vector machines, can be trained on historical data to predict KPIs or stress levels [59]. Once trained, these models can provide statistical insights for debriefings or offer direct feedback to trainees based on their performance relative to predicted KPIs.

Unsupervised learning models, such as clustering algorithms like k-means or hierarchical clustering, can be used to group similar performance data together. This can help identify common characteristics of high-performing trainees, which can then be used to better train other trainees [60]. To provide real-time feedback to trainees, reinforcement learning can be used. The model learns to make decisions based on the reward (or penalty) it receives for its actions, which can be tied to the KPIs. For example, a reinforcement learning model could be used in a training simulation to provide feedback to trainees based on their actions [61].

Deep learning models can be used to analyze more complex patterns in KPI data. For example, recurrent neural networks are great tools to analyze time-series data, while convolutional neural networks can analyze image or video-based KPI data, potentially supporting video analysis during the debriefing of the training [62]. Current challenges in automating the analysis of qualitative data, such as communication and team performance, could be overcome in the future by using natural

language processing models, which can identify key themes and sentiments in speech-to-text-based data [63]. In our current research, we are investigating the feasibility of the abovementioned machine learning models to test their application in MR training and will report results in future research.

An example, showcasing the power of reinforcement learning to adapt virtual scenarios based on trainee performance, has been provided by the research group developing Unity's Machine Learning Agents toolkit [64]. This open-source tool was originally developed to create game-based training environments for training intelligent agents. However, in the context of our research, it could potentially be used to develop a smart trainer assistant that adapts virtual scenarios based on continuous trainee performance analysis.

Furthermore, real-time training analysis opens up new possibilities for scenario adaptation and the development of more personalized training guidelines. Future work will explore these avenues and focus on the development of smart scenario

control features supported by advanced machine learning methods.

Conclusions

In conclusion, this research addresses important gaps in immersive simulation training for MFRs by integrating real-time performance metrics and stress level indicators into MR systems. This innovative approach enhances training by providing objective, actionable insights for both trainers and trainees, emphasizing the crucial role of performance evaluation and stress management in emergency response scenarios. Additionally, the study presents insights into user preferences for stress visualization, highlighting the need for intuitive and user-friendly interfaces. The human-centered design methodology ensures these enhancements align closely with end user requirements. The methodologies and design considerations outlined in this work can serve as a framework for developing interactive and immersive training environments across various high-stress fields, contributing to more effective, efficient, and user-focused training solutions.

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Authors' Contributions

OZ, DP, RW, and QN conceptualized the study; OZ and QN contributed to the methodology; OZ, DP, RW, and QN contributed to validation; OZ and QN performed formal analysis; OZ wrote the original draft; OZ, HS-F, DP, RW, QN, and MT reviewed and edited the manuscript; HS-F and MT contributed to supervision; and HS-F managed project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Interview guide.

[[DOCX File, 492 KB](#) - [xr_v1i1e57655_app1.docx](#)]

Multimedia Appendix 2

Requirements and key performance indicators.

[[XLSX File, 32 KB](#) - [xr_v1i1e57655_app2.xlsx](#)]

Multimedia Appendix 3

MED1stMR survey.

[[PDF File, 1504 KB](#) - [xr_v1i1e57655_app3.pdf](#)]

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Abbreviations

ECG: electrocardiogram
EDA: electrodermal activity
HR: heart rate
HRV: heart rate variability
KPI: key performance indicator
MCI: mass casualty incident
MFR: medical first responder
MR: mixed reality
VR: virtual reality
XR: extended reality

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Original Paper

Immediate Impact of an 8-Week Virtual Reality Educational Program on Burnout and Work Engagement Among Health Care Professionals: Pre-Post Pilot Study

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Abstract

Background: Health care professionals globally face increasing levels of burnout characterized by emotional exhaustion, depersonalization, and a reduced sense of accomplishment, and it has been notably exacerbated during the COVID-19 pandemic. This condition not only impacts the well-being of health care workers but also affects patient care and contributes to significant economic burden. Traditional approaches to mitigating burnout have included various psychosocial interventions, with mindfulness being recognized for its effectiveness in enhancing mental health and stress management. The emergence of virtual reality (VR) technology offers a novel immersive platform for delivering mindfulness and emotional management training.

Objective: This study aimed to evaluate the immediate impact of an 8-week VR educational program on burnout and work engagement among health care professionals.

Methods: This nonrandomized pre-post intervention study enrolled 90 health care professionals, including nurses, physicians, and allied health staff, from 3 different centers. Of these 90 professionals, 83 (92%) completed the program. The intervention consisted of 8 weekly VR sessions of 10-13 minutes each, using Meta Quest 2 headsets. The sessions focused on mindfulness and emotional management. The Maslach Burnout Inventory (MBI) and Utrecht Work Engagement Scale (UWES) were used for assessments. Data analysis involved inferential statistical techniques for evaluating the impact on the scales, including paired *t* tests for normally distributed variables and Wilcoxon signed rank tests for nonnormally distributed variables. The significance of changes was indicated by *P* values <.05, with effect sizes measured using Cohen *d* for *t* tests and Cohen *r* for Wilcoxon tests for quantifying the magnitude of the intervention's effect.

Results: The statistical analysis revealed significant improvements in the MBI and UWES indices after the intervention (*P*<.05). Specifically, the MBI showed reductions in emotional exhaustion ($t_{82}=5.58$; *P*<.001; Cohen *d*=0.61) and depersonalization ($t_{82}=4.67$; *P*<.001; Cohen *d*=0.51), and an increase in personal accomplishment ($t_{82}=-3.62$; *P*<.001; Cohen *d*=0.4). The UWES revealed enhancements in vigor ($t_{82}=-3.77$; *P*<.001; Cohen *d*=0.41), dedication ($Z=-3.63$; *P*<.001; Cohen *r*=0.41), and absorption ($Z=-3.52$; *P*<.001; Cohen *r*=0.4).

Conclusions: The study provides initial data supporting the effectiveness of VR-based educational programs for reducing burnout and enhancing work engagement among health care professionals. While limitations, such as the absence of a control group, are acknowledged, the significant improvements in burnout and engagement indices coupled with high participant adherence and minimal VR discomfort underline the potential of VR interventions in health care settings. These encouraging findings pave the way for more comprehensive studies, including randomized controlled trials, to further validate and expand upon these results.

KEYWORDS

virtual reality; burnout; mindfulness; health care professionals; mental health; health promotion; educational intervention

Introduction

Background

Burnout among health care workers is a growing concern that affects professionals worldwide. Burnout is characterized by emotional exhaustion, depersonalization, and a diminished sense of personal accomplishment [1], and it extends beyond transient workplace stress, potentially undermines patient care quality, increases the rate of errors, creates a negative work climate, and contributes to health care costs [1-3]. The prevalence of burnout varies considerably, with a scoping review during the COVID-19 pandemic reporting rates of 4.3% to 90.4% among health care workers, reflecting the significant mental burden and high levels of stress and burnout experienced by frontline health care workers during this period [4]. This review highlighted multiple factors associated with increases or decreases in burnout, including demographic characteristics, psychological conditions, social factors, work organization, and direct COVID-19-related impacts, providing valuable insights for policy makers and health care managers [4].

The COVID-19 pandemic has notably worsened this panorama, causing unprecedented spikes in burnout rates. Data from Spain [5] revealed an increase from 10% before the pandemic to a staggering 50% during the pandemic, with a marked rise in emotional exhaustion and depersonalization, and a decline in personal accomplishment among primary care physicians.

Economically, burnout contributes to substantial costs in the health care system, with estimates in the United States indicating a US \$979 million annual burden related to turnover and reduced clinical hours among primary care physicians alone [6,7]. To deal with this issue, the World Health Organization has underscored the importance of psychosocial interventions, including mindfulness and cognitive behavioral strategies, to enhance mental health and stress management in the workplace [8].

Contemporary research supports mindfulness as an effective intervention against burnout [9,10]. This practice, originally encapsulated by Kabat-Zinn's [11] conceptualization as an intentional nonjudgmental focus on the present experience, is gaining recognition as a cornerstone in the arsenal against burnout among medical professionals [12]. The implementation of mindfulness is corroborated by evidence indicating its significant contribution to bolstering emotional resilience, fostering effective communication, and reinforcing collaborative dynamics in the often high-pressure clinical environment [13-15].

Integration of Mindfulness Practices in Health Care Through Virtual Reality Technology

With the integration of technology into health care, virtual reality (VR) offers a novel platform for mindfulness training. By simulating controlled environments, VR can deepen

mindfulness practices, potentially surpassing traditional methods in improving mood, sleep quality, and cognitive focus [16]. The immersive experiences of VR are known to increase knowledge retention and engagement, making educational interventions more effective [17-22].

The application of VR to mindfulness training presents a unique opportunity for health care professionals to cultivate skills for managing stressors inherent to their profession. Empirical evidence suggests that VR-based mindfulness can yield significant benefits for emotional regulation and stress reduction, thus improving the well-being of health care providers [23-26].

Study Objective and Hypothesis

The objective of this pilot study was to evaluate the immediate impact of an 8-week VR educational program on burnout and work engagement among health care professionals. The study measured changes in the levels of emotional exhaustion, depersonalization, and personal accomplishment as characterized by the Maslach Burnout Inventory (MBI), along with the dimensions of vigor, dedication, and absorption as depicted by the Utrecht Work Engagement Scale (UWES).

The study was guided by 2 hypotheses. The null hypothesis (H0) proposed that the VR educational program would not result in significant changes in burnout or work engagement levels, and any variations could be attributed to random fluctuation rather than the intervention's effect. Conversely, the alternative hypothesis (H1) suggested that the VR program would lead to significant improvements in these measures, reflecting a direct positive impact of the intervention on the professional well-being of participants.

While burnout is recognized as a multifaceted syndrome influenced by a variety of factors, the project posited that a targeted VR program focusing on mindfulness and emotional management might enhance resilience among health care professionals. This resilience, in turn, could modify their perception and coping mechanisms, equipping them with effective strategies to counteract work-related stress. The insights gained from this study are expected to contribute to the development of innovative and more personalized interventions that are tailored to the needs of health care workers [25,26].

Methods

Study Design

In this prospective interventional pilot study, a nonrandomized pre-post intervention design was used to explore the preliminary effects of a mindfulness-based VR educational program in health care professionals.

Participants and Setting

This pilot study enrolled 90 health care professionals, representing a broad range of specialties in the health care sector. The demographic profile of the 83 participants who completed

the program revealed an average age of 46.39 years and a mean professional tenure of 17.57 years. The cohort was predominantly female, with only 7 male participants, reflecting the sex distribution that is common in these centers. The detailed breakdown of professional roles within the cohort is presented in the Results section.

Selection and Enrollment

Recruitment

Recruitment for the study was conducted via an open invitation across 3 health care centers, and the study targeted a diverse group of professionals, including nurses, physicians, administrative staff, nursing assistants, occupational therapists, social workers, psychologists, pediatricians, dentists, and ward assistants.

The first, second, and third centers have been identified in this study as CAP-A, CAP-B, and CSSC, respectively. Informative sessions were held in each center during the recruitment of each group owing to different time periods. During these sessions, all professionals were able to ask questions about VR and the program, and later decide if they were interested in participating. If interested, they were required to send an email to our team to be evaluated for inclusion.

The absence of a control group in this study was a strategic choice, which was influenced by the exploratory nature of the pilot study and resource limitations. This choice and its implications are further discussed in the Limitations subsection. The study's pre-post design without a control group necessitated a sample size that was feasible within the available resources and anticipated participant availability.

Inclusion and Withdrawal Criteria

Health care professionals who were currently employed in the study centers, older than 18 years, and able to commit to the program's full duration were considered for inclusion. Informed consent was required, along with a commitment to complete all questionnaires. Participants were excluded if they had participated in a similar program or received specific training in burnout prevention within the last 12 months, had a long-term absence from work or any situation that prevented regular attendance during the study, or had vertigo, epilepsy, or significant visual/auditory disabilities that precluded the use of VR glasses. Withdrawal from the study was considered when participants had significant intolerance to VR equipment or were absent for more than two sessions. To facilitate participation and minimize dropout, participants were allowed a 2-week grace period after the program to cover any missed sessions.

Sequential Enrollment, Center Allocation, and Attrition

Enrollment and participation were conducted in sequential phases to accommodate the limited number of VR headsets, with only 2 headsets available for the entire study. The initial enrollment occurred at the first center (CAP-A) in February 2022, with 29 participants included and then divided randomly into 3 groups for logistic reasons. The groups completed the program at different times throughout the year, with the final group concluding in December 2022.

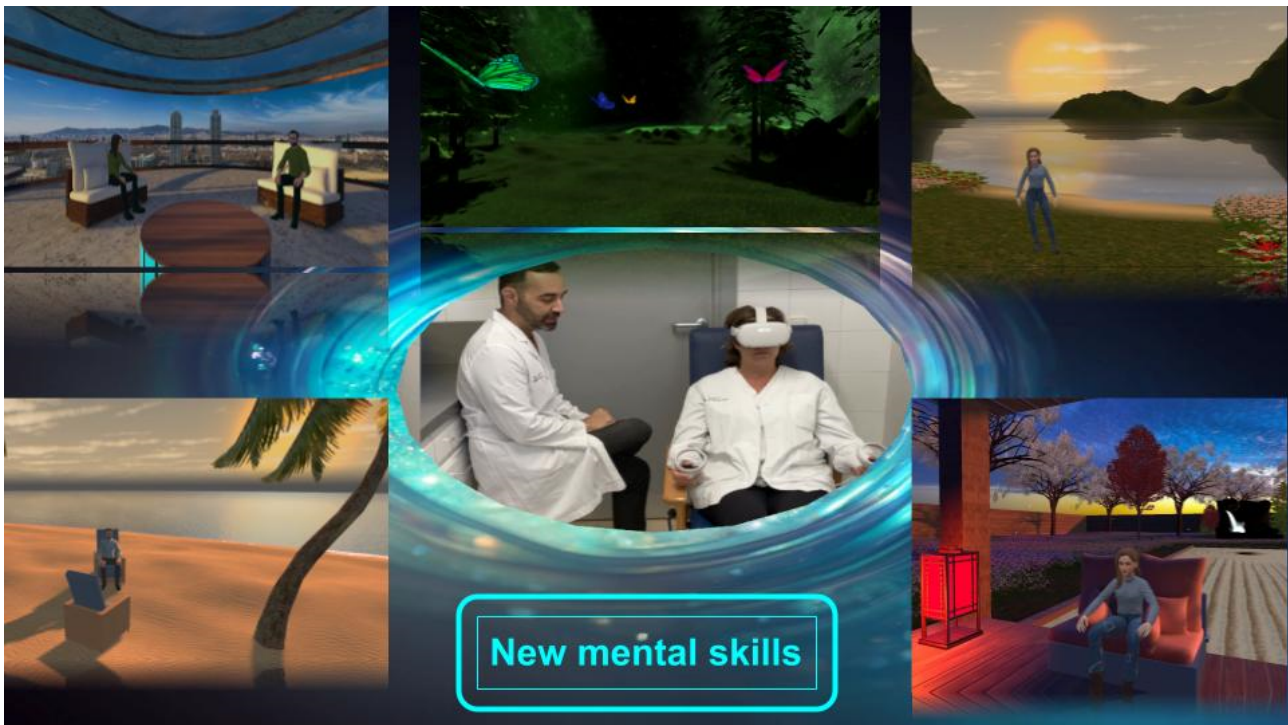
Building on the lessons learned from the initial phase regarding resource utilization and scheduling, the process was refined for subsequent enrollments. In 2023, a more streamlined approach was adopted at the next 2 centers, where all participants were enrolled in a single group per center to simplify logistics. Recruitment for the study was conducted simultaneously at both centers in January and February 2023. At CSSC, 41 participants were included, with 36 participants successfully completing the program between February and April 2023. At CAP-B, 20 participants were initially enrolled, with 14 participants completing the program in April and a small additional group of 4 participants completing the program in October 2023.

Instruments

The intervention was delivered through Meta Quest 2 VR headsets (Meta Platforms, Inc), which were chosen for their cable-free stand-alone functionality and high-quality audiovisual output. The headsets feature hand tracking capabilities that were used in the program to enhance immersion by visualizing users' hands in VR and allowing simple selection of sessions via the menu. The program was developed between April 2021 and January 2022 following a methodical approach based on bibliographic review and guided by the expertise of author NM. It integrated mindfulness and emotional management techniques, which are well-established methods for reducing burnout and enhancing work engagement, and are particularly beneficial in health care settings [9-26]. The VR sessions were developed by author JFC. VR technology was integrated with the author's clinical expertise in mindfulness to create a dynamic learning environment. Unity (Unity Technologies) and Blender (Blender Foundation) were used to construct 3D animations that visually represent and illustrate mindfulness and emotion management techniques. These animations serve as immersive educational tools within VR environments, enhancing the learning experience beyond traditional relaxation sessions. Moran Bueno, who specializes in mindfulness at the University of Barcelona, ensured that the content was scientifically accurate and pedagogically effective. The development process involved iterative feedback from health care professionals, aiming to refine the program's educational impact and comfort. The VR environments were specifically crafted for passive educational engagement, allowing participants to immerse in the program without the need for active interaction or physical movement and thus enhancing the learning experience in a safe and user-friendly manner. The VR program allowed for a more engaging and potentially more impactful learning experience by placing participants in various virtual environments that can enhance the absorption of the techniques taught.

The VR sessions immersed participants in various carefully designed settings, such as a serene beach, calm lake, and peaceful Zen garden. Ambient sounds corresponding to each environment, like the soothing lapping of waves, were incorporated to deepen the sensory experience. This auditory enhancement, in tandem with visual elements, augmented the overall educational and immersive quality for the users. The integration of these sensory aspects aimed to create an optimal learning environment for engaging with the mindfulness and emotional management content (Figure 1).

Figure 1. Some of the virtual reality environments of the educational program. Displayed images from the top middle in clockwise direction are butterflies in a garden, a serene bay, a zen garden, a tropical beach, and a terrace with panoramic views of Barcelona. At the center is an image of a supervised session in progress.



VR Considerations

Although VR is a technological tool with minimal risk, the use of VR headsets, especially for extended periods, can occasionally lead to side effects, such as cybersickness, eye strain, emotional reactions, and physical danger, in some individuals [20,27-30]. These potential effects were carefully considered in the design of the intervention to minimize any adverse outcomes. The potential side effects are as follows [27,30]:

- **Cybersickness:** Symptoms include nausea, balance issues, disorientation, headache, eye strain, and general fatigue, which tend to dissipate shortly after the discontinuation of VR use.
- **Eye strain:** Eye discomfort may occur with extended VR use, although such instances are uncommon given the brevity of typical exposure times in a controlled research setting.
- **Intense emotional reactions:** The compelling realism of VR and the emotion-related content can provoke emotional responses, requiring monitoring.
- **Physical danger:** While rare in a controlled environment, there is a potential risk of physical injury due to loss of spatial awareness while immersed in VR. This includes the possibility of tripping, bumping into objects, or other accidents, particularly if the physical space is not adequately prepared for VR activities.

Mitigation Measures

The project development incorporated strategic measures to address human factors and ergonomic considerations, aiming to minimize VR-induced side effects. These measures, which aligned with current guidelines and best practices, were

meticulously designed to ensure the safety and efficacy of the VR intervention [27-30]. The design aspects are as follows:

- **Session duration:** VR sessions are capped at 10-13 minutes, reducing the risk of cybersickness and visual fatigue [27].
- **Static interaction:** Design of the VR experience for seated participants (minimal requirement for movement) reduces the risks of nausea and physical activity in VR [28,29].
- **Hand tracking:** Incorporation of hand tracking technology allows participants to maintain a sense of agency and immersion in the VR environment without necessitating complex interactions [28,29].
- **Optimization of the VR content:** VR content is carefully designed to avoid overly intense stimuli and to support user comfort. Adjustments to lighting, motion, and frame rates are considered to prevent disorientation and discomfort [27,30].
- **Stress relief features:** Elements, such as biophilic designs, soft colors, and calming music within the VR environment, are incorporated to create a restorative virtual space for users [27].
- **Monitoring and support:** Continuous observation during VR exposure and immediate follow-up after VR exposure permits the research team to identify and mitigate any adverse effects. Participants are advised on headset adjustment and encouraged to take breaks as needed [27,29].
- **User training:** Prior to the initiation of the VR educational program, participants need to undergo a training session focused on VR utilization. This session includes instructions on the proper adjustment of the VR headset, acclimatization to immersive experiences, navigation of the VR interface, and response to potential side effects. The aim is to foster participant independence in managing the VR system and to ensure comfort during use [29].

This approach not only aids in minimizing potential motion-induced discomfort but also ensures a consistent and comfortable experience for all participants. During the course of the research, no VR-related side effects were observed. The only concern reported by a small subset of participants ($n=7$) was discomfort attributed to the weight of the headset. In most instances, this was alleviated, at least partially, by readjusting the headset. Regular check-ins were conducted after the sessions to monitor any adverse effects, and guidance was provided to participants on taking breaks or adjusting the headset position as needed, which further contributed to the positive reception and comfort of the intervention.

Procedure

The program lasted for 8 weeks. A calendar was created, and each participant was assigned a specific day and time every week for their 13-minute VR session. Each session was designed with a clear structure, consisting of 3 phases: preparation, VR experience, and cleanup. In order to ensure a secure and efficient implementation of the program, the sessions were conducted under the supervision of one of the researchers. During the preparation phase, participants were welcomed and assisted with the VR headset adjustment. The role of the researcher included monitoring the implementation for consistency, managing any technical issues, and ensuring that the VR equipment was used safely and effectively.

A key advantage of this VR program is that it constitutes a fully self-contained system. The VR content was directly uploaded to the headsets, thereby eliminating dependency on internet connectivity, an essential feature for accommodating health care professionals operating in environments where internet access may be limited or nonexistent.

Content Overview

Over the sessions, participants engaged with content from the following primary areas:

- **Mindfulness training:** In these sessions, exercises are focused on breath and body scanning, aiming to ground participants in the present moment. By maintaining an attitude of acceptance and nonjudgment, these sessions aim to teach how to foster mental tranquility.
- **Emotional regulation:** In these sessions, participants are introduced to techniques designed to address and manage intense emotions. Instead of suppressing or avoiding discomforting feelings, participants are encouraged to approach them with openness and curiosity, potentially deriving insights and understanding from their observations.
- **Self-compassion:** This area underscores the importance of treating oneself with kindness, especially during challenging times. Recognizing and minimizing the influence of one's inner critic is crucial. Participants are taught to treat themselves with the same warmth and understanding they would extend to a close friend or loved one, promoting a balanced self-view.

Variables

The study evaluated the intervention's impact using demographic and psychometric assessments. Demographic data

collected included age, sex, professional category, and tenure, to understand sample characteristics and control for confounding factors. Psychometric evaluation was performed with 2 established tools: MBI and UWES. These 2 scales were administered on paper before the commencement of the first session and after the conclusion of the last session. Both scales score their 3 subdimensions on a Likert scale from 0 (never) to 6 (daily).

The MBI is an established instrument for assessing burnout in health care settings, and it uses 3 subscales, namely, emotional exhaustion, depersonalization, and personal accomplishment, to capture burnout dimensions. Its high reliability has been confirmed with Cronbach α coefficients ranging from 0.71 to 0.90 in the Spanish health care context, validating its use for this study [31-36].

The subscales are interpreted as follows [36]:

- **Emotional exhaustion:** A score of ≥ 27 indicates a high level of burnout, 19-26 indicates a moderate level of burnout, and < 19 indicates a low level of burnout.
- **Depersonalization:** A score of > 10 indicates a high degree of depersonalization, 6-9 indicates a moderate degree of depersonalization, and < 6 indicates a low degree of depersonalization.
- **Personal accomplishment:** A score of 0-30 suggests a low degree of personal accomplishment, 34-39 suggests a moderate degree of personal accomplishment, and > 40 suggests a high degree of personal accomplishment.

The UWES is a questionnaire that measures work engagement through 3 aspects: vigor, dedication, and absorption, which are defined by high energy, a sense of significance, and deep involvement in work, respectively. Scores on the UWES are calculated as mean values across the items for each dimension. Based on these mean scores, engagement levels are categorized into 5 distinct groups: very low, low, medium, high, and very high. This categorization allows for a nuanced understanding of work engagement among participants. The UWES shows robust psychometric properties for Spanish medical professionals, with a Cronbach α total reliability score of 0.93 and strong subscale consistencies. It has been proven to be effective for correlating work engagement with health outcomes and job stress, making it a pertinent choice for assessing the positive occupational states in the study [37-40].

Ethical Considerations

This study was conducted in compliance with the principles outlined in the Declaration of Helsinki (1964) for research involving human subjects, as evaluated and approved by the Badalona Serveis Assistencials' Research Committee and the Jordi Gol i Gurina Foundation Ethics Committee (approval number: 21/280-P). The committees conducted an ethical review of the project, which included consideration of participant confidentiality, informed consent, and potential risks to participants.

Statistical Analysis

Data Anonymization and Blinding

To protect participant confidentiality while ensuring data integrity, each data set was pseudoanonymized with an identifier code. This measure allowed for an individual response to be tracked without revealing personal information. The principal investigator was the sole individual with access to the decryption key, thus reinforcing the partial blinding of research staff and minimizing potential biases. Statistical analysis was performed with DATAtab (DATAtab e.U.) and SPSS Version 27 (IBM Corp).

Normality Tests

The Shapiro-Wilk test was used to determine the distribution of each variable, a necessary step to guide the selection of appropriate statistical tests for the subsequent analyses.

Inferential Statistical Analysis and Hypothesis Testing

Following the descriptive summary of the data, inferential statistical analyses were conducted to test the study's hypothesis that the VR educational program would lead to significant changes in burnout and work engagement scores. The paired *t* test was applied to normally distributed variables to determine if the mean differences in scores before and after the intervention were statistically significant. For data that did not meet the criteria for normal distribution, the Wilcoxon signed-rank test was used to assess median score differences. All tests set the significance threshold at $P < .05$.

Table 1. Demographic profile of the study participants.

| Professional category | Participants, n | Age (years), mean | Age (years), range | Sex (female/male), n | Tenure (years), mean | Tenure (years), range |
|-------------------------|-----------------|-------------------|--------------------|----------------------|----------------------|-----------------------|
| Nurses | 30 | 44.93 | 29-56 | 27/3 | 18.90 | 2-34 |
| Physicians | 15 | 50.80 | 39-63 | 12/3 | 15.33 | 2-32 |
| Administrative staff | 13 | 48.92 | 35-59 | 12/1 | 16.69 | 1-36 |
| Nursing assistants | 7 | 45.43 | 27-58 | 7/0 | 17.43 | 1-29 |
| Occupational therapists | 7 | 46.43 | 41-57 | 7/0 | 24.86 | 18-42 |
| Social workers | 3 | 41.33 | 40-43 | 3/0 | 7.33 | 1-16 |
| Psychologists | 3 | 39.33 | 28-47 | 3/0 | 17.67 | 15-21 |
| Pediatricians | 2 | 36.00 | 33-39 | 2/0 | 7.25 | 3.5-11 |
| Dentists | 2 | 45.00 | 41-49 | 2/0 | 19.00 | 13-25 |
| Ward assistants | 1 | 57.00 | 57 | 1/0 | 21.00 | 21 |
| Overall | 83 | 46.39 | 27-63 | 76/7 | 17.57 | 1-42 |

Descriptive Statistics

Upon establishing the distribution characteristics of the data set, descriptive statistics summarized the data for the 83

Results

Demographics

Attrition resulted in a final sample of 83 participants who completed the intervention (5 dropouts from CSSC and 2 from CAP-B; CAP-A retained all its participants). The study achieved a high participation rate of 92% (83/90). Attrition was due to personal circumstances not related to the VR system. Specifically, 1 participant was on maternity leave, 3 were on sick leave, and 3 cited time constraints as the reason for withdrawal. Notably, there were no dropouts attributed to discomfort or adverse reactions to the VR technology.

The demographic characteristics of the participants are summarized in [Table 1](#). The final sample consisted of 83 health care professionals with an average age of 46.39 (range 27-63) years. The cohort included 30 nurses, 15 physicians, and individuals with various other roles such as administrative staff and nursing assistants. Female participants represented the majority of the sample, with 76 female participants compared to 7 male participants. The mean tenure was 17.57 years, with individual tenures ranging from 1 to 42 years, reflecting a wide range of professional experience among the participants. These demographic data offer a comprehensive overview of the study sample, highlighting the diversity in age, professional role, and experience within the health care setting.

participants who completed the VR educational program. The analysis provided an initial overview of the results ([Table 2](#)).

Table 2. Descriptive statistics of the Maslach Burnout Inventory and Utrecht Work Engagement Scale items among the 83 study participants.

| Variable | Mean | Median | SD | Minimum | Maximum |
|--------------------------------|-------|--------|-------|---------|---------|
| Emotional exhaustion | | | | | |
| Preintervention | 22.67 | 21 | 10.88 | 2 | 51 |
| Postintervention | 17.07 | 17 | 9.00 | 0 | 42 |
| Depersonalization | | | | | |
| Preintervention | 10.04 | 10 | 5.07 | 0 | 24 |
| Postintervention | 7.37 | 7 | 4.34 | 0 | 20 |
| Personal accomplishment | | | | | |
| Preintervention | 29.72 | 30 | 8.64 | 1 | 47 |
| Postintervention | 33.08 | 34 | 6.70 | 17 | 46 |
| Vigor | | | | | |
| Preintervention | 22.90 | 23 | 5.91 | 8 | 35 |
| Postintervention | 24.41 | 24 | 5.65 | 8 | 36 |
| Dedication | | | | | |
| Preintervention | 18.72 | 19 | 6.43 | 6 | 30 |
| Postintervention | 20.36 | 22 | 5.88 | 8 | 30 |
| Absorption | | | | | |
| Preintervention | 19.86 | 21 | 6.58 | 6 | 32 |
| Postintervention | 21.71 | 23 | 6.39 | 6 | 35 |

Efficacy of the VR Educational Program

Descriptive Analysis

An analysis of MBI and UWES scores after the VR program reflects a potential impact on participants' professional well-being. [Multimedia Appendix 1](#) presents data indicating a dual effect. There was a reduction in burnout as evidenced by lower emotional exhaustion and depersonalization scores, alongside increased feelings of personal accomplishment. Simultaneously, elevated vigor, dedication, and absorption scores indicated augmented work engagement following the VR intervention.

Following the descriptive analysis, [Table 3](#) provides a detailed breakdown of the distribution of burnout levels among participants both before and after the intervention. The table categorizes participants into low, moderate, and high levels of burnout for each of the following 3 MBI subscales: emotional exhaustion, depersonalization, and personal accomplishment. It presents these categories in both percentage and actual number of participants, offering a clear perspective on the shift in burnout levels after the intervention among the 83 health care professionals involved in the study.

Table 3. Distribution of burnout levels among the 83 study participants before and after the intervention.

| Variable | High burnout, n (%) | Moderate burnout, n (%) | Low burnout, n (%) |
|--------------------------------|---------------------|-------------------------|--------------------|
| Emotional exhaustion | | | |
| Preintervention | 27 (33) | 24 (29) | 32 (39) |
| Postintervention | 10 (12) | 20 (24) | 53 (64) |
| Depersonalization | | | |
| Preintervention | 45 (54) | 21 (25) | 17 (21) |
| Postintervention | 21 (25) | 34 (41) | 28 (34) |
| Personal accomplishment | | | |
| Preintervention | 44 (53) | 26 (31) | 13 (16) |
| Postintervention | 29 (35) | 40 (48) | 14 (17) |

Statistical Comparisons and Significance

Shapiro-Wilk tests were used to determine the normality of all variables. Emotional exhaustion, depersonalization, personal accomplishment, and vigor, which followed a normal distribution, were analyzed using *t* tests. The nonnormally distributed variables dedication and absorption were analyzed using the Wilcoxon test. Additionally, effect sizes were calculated using Cohen *d* for normally distributed data and Cohen *r* for nonnormally distributed data to quantify the magnitude of observed changes.

Correlation and Effect Size Assessments

Correlation assessments were integral to the analysis in order to evaluate relationships between preintervention and postintervention scores. The Pearson correlation was applied to normally distributed data, and the Spearman correlation was used for nonnormally distributed data, with findings reported in Tables 4 and 5. The Cohen *d* and *r* have been provided to reflect the effect sizes and assess the strength of differences, with statistically significant changes ($P < .05$) in all variables.

Table 4. Summary of preintervention and postintervention analysis results for normally distributed variables.

| Variable | Preintervention result, mean (SD) | Postintervention result, mean (SD) | <i>t</i> test <i>t</i> (<i>df</i>) | <i>P</i> value (2-tailed) | Effect size, Cohen <i>d</i> | Pearson <i>r</i> | Pearson <i>P</i> |
|-------------------------|-----------------------------------|------------------------------------|---|---------------------------|-----------------------------|------------------|------------------|
| Emotional exhaustion | 22.67 (10.88) | 17.07 (9.00) | 5.58 (82) | <.001 | 0.61 | 0.59 | <.001 |
| Depersonalization | 10.04 (5.07) | 7.37 (4.34) | 4.67 (82) | <.001 | 0.51 | 0.40 | <.001 |
| Personal accomplishment | 29.72 (8.64) | 33.08 (6.70) | -3.62 (82) | <.001 | 0.40 | 0.41 | <.001 |
| Vigor | 22.65 (5.98) | 24.66 (5.50) | -3.77 (82) | <.001 | 0.41 | 0.64 | <.001 |

Table 5. Summary of preintervention and postintervention analysis results for nonnormally distributed variables.

| Variable | Preintervention result, median (IQR) | Postintervention result, median (IQR) | Wilcoxon test | | | Effect size, Cohen <i>r</i> | Spearman <i>r</i> | Spearman <i>P</i> |
|------------|--------------------------------------|---------------------------------------|---------------|----------|---------------------------|-----------------------------|-------------------|-------------------|
| | | | <i>W</i> | <i>z</i> | <i>P</i> value (2-tailed) | | | |
| Dedication | 19 (12) | 22 (8) | 580 | -3.63 | <.001 | 0.41 | 0.73 | <.001 |
| Absorption | 20 (10) | 23 (9.5) | 785.5 | -3.52 | <.001 | 0.40 | 0.67 | <.001 |

Epidemiologic Factors

Spearman correlation analysis was employed to explore relationships between age, tenure, and the main study variables, and it revealed no significant correlations. Similarly, point biserial correlation analysis indicated no significant correlations between sex and the study variables both before and after the intervention.

The influence of professional categories on questionnaire outcomes was assessed using η^2 values (Table 6). The η^2 values ranged from 0.01 to 0.24 and indicated the proportion of variance in each measure that can be attributed to the professional category. Higher η^2 values, such as those for

preintervention depersonalization, suggested a more significant variance related to the professional category, while other measures exhibited a lower degree of variance due to professional categorization, reflecting a range of impacts across different professional categories.

The ANOVA analysis provided deeper insights into the intervention's impact, examining changes in the MBI and UWES scores. This analysis encompassed overall changes and variations across different professional categories. Detailed statistical outcomes, including sums of squares, mean squares, *F* values, and *P* values, are presented in Table 7, highlighting the statistical significance of the observed changes.

Table 6. Maslach Burnout Inventory and Utrecht Work Engagement Scale data across different professional categories.

| Professional category | Emotional exhaustion, mean (SD) | | Depersonalization, mean (SD) | | Personal accomplishment, mean (SD) | | Vigor, mean (SD) | | Dedication, mean (SD) | | Absorption, mean (SD) | |
|-------------------------|---------------------------------|-------------------|------------------------------|-----------------|------------------------------------|-----------------|------------------|-----------------|-----------------------|-----------------|-----------------------|-----------------|
| | Pre ^a | Post ^b | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| Nurses | 20.37 (8.78) | 18.77 (8.22) | 9.97 (4.43) | 8.00 (4.10) | 30.03 (8.26) | 33.73 (7.23) | 21.90 (6.83) | 23.37 (5.84) | 18.57 (6.78) | 20.23 (5.66) | 19.40 (7.37) | 21.37 (6.35) |
| Physicians | 26.13 (12.70) | 19.93 (9.90) | 10.13 (4.66) | 7.80 (4.72) | 29.40 (5.59) | 31.53 (7.62) | 21.60 (5.33) | 24.60 (5.26) | 18.33 (6.20) | 21.60 (5.53) | 20.80 (6.11) | 24.07 (4.38) |
| Administrative staff | 22.00 (7.97) | 15.77 (9.36) | 13.15 (3.93) | 8.00 (4.81) | 27.23 (8.63) | 31.23 (5.95) | 24.00 (4.93) | 27.08 (4.96) | 16.38 (6.46) | 18.69 (6.13) | 19.77 (6.31) | 22.31 (7.09) |
| Nursing assistants | 22.43 (10.50) | 16.00 (12.49) | 11.00 (4.90) | 7.71 (4.54) | 25.29 (14.28) | 32.00 (8.70) | 23.29 (6.42) | 26.14 (6.15) | 20.43 (7.28) | 21.43 (6.85) | 19.00 (7.79) | 22.14 (7.65) |
| Occupational therapists | 17.86 (12.42) | 10.57 (4.08) | 9.14 (7.36) | 4.57 (2.23) | 33.43 (6.75) | 35.43 (2.64) | 25.00 (6.08) | 24.57 (4.72) | 20.43 (7.74) | 21.29 (4.75) | 19.00 (6.93) | 19.57 (7.59) |
| Psychologists | 36.33 (4.16) | 14.33 (6.03) | 3.00 (3.61) | 3.33 (1.53) | 27.67 (10.21) | 35.67 (5.03) | 22.33 (2.89) | 26.67 (1.53) | 21.67 (2.52) | 22.00 (1.00) | 21.33 (9.81) | 23.33 (6.35) |
| Social workers | 15.33 (8.08) | 11.67 (6.81) | 2.67 (2.52) | 4.33 (4.51) | 35.67 (12.70) | 33.33 (8.14) | 19.67 (7.57) | 23.00 (5.57) | 18.67 (10.21) | 20.33 (8.08) | 20.33 (8.14) | 22.33 (6.43) |
| Pediatricians | 43.50 (10.61) | 27.00 (5.66) | 13.50 (2.12) | 11.50 (7.78) | 29.00 (5.66) | 33.00 (4.24) | 23.50 (6.36) | 17.00 (4.24) | 16.00 (5.66) | 12.50 (4.95) | 18.00 (5.66) | 17.00 (2.83) |
| Ward assistants | 26.50 (20.51) | 12.50 (6.36) | 10.50 (6.36) | 5.50 (3.54) | 38.00 (11.31) | 38.00 (4.24) | 25.00 (9.90) | 28.00 (4.24) | 23.00 (7.07) | 21.50 (4.95) | 18.50 (7.78) | 21.00 (7.07) |
| Dentists | 16.00 (N/A ^c) | 7.00 (N/A) | 5.00 (N/A) | 8.00 (N/A) | 36.00 (N/A) | 34.00 (N/A) | 26.00 (N/A) | 31.00 (N/A) | 19.00 (N/A) | 27.00 (N/A) | 17.00 (N/A) | 21.00 (N/A) |
| η^d | 0.47 | 0.39 | 0.49 | 0.35 | 0.32 | 0.24 | 0.23 | 0.37 | 0.23 | 0.31 | 0.12 | 0.24 |
| η^{2d} | 0.22 | 0.15 | 0.24 | 0.13 | 0.1 | 0.06 | 0.05 | 0.14 | 0.05 | 0.09 | 0.01 | 0.06 |

^aPre: preintervention.^bPost: postintervention.^cN/A: not applicable.^d η and η^2 values indicate the variance due to professional categorization.

Table 7. ANOVA results for preintervention and postintervention measures and professional categories.

| Variable | Sum of squares | Degrees of freedom (<i>df</i>) | Mean squares | <i>F</i> | <i>P</i> value |
|----------------------------------|----------------|----------------------------------|--------------|----------|----------------|
| Emotional exhaustion | | | | | |
| Preintervention/postintervention | 1302.56 | 1 | 1302.56 | 37.07 | <.001 |
| Professional category | 2294.19 | 9 | 254.91 | 1.75 | .09 |
| A×B | 861.83 | 9 | 95.76 | 2.73 | .008 |
| Depersonalization | | | | | |
| Preintervention/postintervention | 294.22 | 1 | 294.22 | 21.89 | <.001 |
| Professional category | 567.48 | 9 | 63.05 | 2.33 | .02 |
| A×B | 126.04 | 9 | 14.00 | 1.04 | .42 |
| Personal accomplishment | | | | | |
| Preintervention/postintervention | 468.92 | 1 | 468.92 | 12.37 | .001 |
| Professional category | 656.22 | 9 | 72.91 | 0.86 | .57 |
| A×B | 168.51 | 9 | 18.72 | 0.49 | .87 |
| Vigor | | | | | |
| Preintervention/postintervention | 168.01 | 1 | 168.01 | 14.59 | <.001 |
| Professional category | 360.04 | 9 | 40.00 | 0.72 | .69 |
| A×B | 131.10 | 9 | 14.57 | 1.27 | .27 |
| Dedication | | | | | |
| Preintervention/postintervention | 128.41 | 1 | 128.41 | 13.11 | .001 |
| Professional category | 358.90 | 9 | 39.88 | 0.58 | .81 |
| A×B | 84.81 | 9 | 9.42 | 0.96 | .48 |
| Absorption | | | | | |
| Preintervention/postintervention | 208.41 | 1 | 208.41 | 12.78 | .001 |
| Professional category | 194.98 | 9 | 21.66 | 0.29 | .98 |
| A×B | 34.49 | 9 | 3.83 | 0.24 | .99 |

Discussion

Principal Findings

In this pilot study, we implemented an 8-week VR educational program focused on mindfulness and emotional management for health care professionals. The results suggest that the program can positively affect burnout symptoms and work engagement in this group. This inference is drawn from the significant reductions observed in burnout symptoms and enhancements in work engagement metrics after the intervention (Tables 2-5 and Multimedia Appendix 1). Complementing the observed reductions in burnout symptoms, the VR educational program also appears to have positively influenced work engagement (Tables 4 and 5). These shifts are especially prominent in the dimensions of dedication and absorption, highlighting the VR program's potential in enhancing aspects of work engagement that relate to a sense of significance and deep involvement in work.

The reduction in score variability after the intervention, as shown in Tables 4 and 5, implies a standardized effectiveness of the VR program in mitigating burnout symptoms. This

uniform decrease in scores like emotional exhaustion and depersonalization scores highlights the VR program's consistent impact across participants. The effect sizes, as analyzed from Tables 4 and 5, reveal a more significant impact of the VR intervention in reducing negative burnout aspects, particularly emotional exhaustion and depersonalization, than in enhancing positive work attributes.

Differential Impact Across Professional Categories

The VR program's effects varied among health care roles, as seen in the η^2 values in Table 6. High variability in emotional exhaustion and depersonalization suggests that roles like psychologists and pediatricians might be more vulnerable to certain burnout aspects. Conversely, measures like vigor and absorption showed more uniform responses across roles. The ANOVA analysis revealed significant variation for emotional exhaustion across categories, emphasizing the need for tailored interventions in health care (Table 7). However, the findings should be approached cautiously due to the limited sample size in some categories, needing further research for conclusive results.

Comparison With Prior Work

The improvement in positive occupational states is a key outcome, given the critical role of engagement in the overall well-being and job performance of health care professionals [41]. The successful application of VR in mindfulness and emotional management training is consistent with existing literature [12,13], underscoring its potential as a vital psychosocial intervention tool in health care settings. This aligns with the findings of Lee and Cha [42], indicating the need for refined VR strategies to balance reducing burnout and boosting work engagement in health care.

Strengths and Implications

This pilot study has significant strengths and yields insights with practical implications for addressing burnout in health care professionals. The low dropout rate reinforces user engagement and the potential of VR as a sustainable educational tool, as observed in other research efforts [14-16,43]. The adherence rate of 92% (83/90) along with minimal reports of discomfort from VR use demonstrates its viability in a clinical setting. These factors are encouraging, especially considering the need for ergonomic consideration highlighted by the ease of resolving discomfort with simple adjustments.

The study's VR intervention was designed with a focus on user comfort, drawing from the mitigation strategies outlined in the VR Considerations subsection of the Methods section. This careful design likely contributed to the positive reception and ease of use reported by participants, underscoring the potential of VR in supporting World Health Organization-endorsed strategies for stress management in clinical environments [8].

Limitations

The promising results obtained in this pilot study must be viewed within the context of some methodological constraints. First, the lack of a control group in the study design precludes a definitive conclusion regarding the causality of observed changes, suggesting that further studies with control groups are necessary to corroborate the VR program's effectiveness. Second, the reliance on convenience sampling poses a risk for selection bias, and future studies may benefit from randomized sampling to ensure broader applicability of the results. Third, the study's participant demographic, with a significant underrepresentation of male participants, reflects the female majority typical in health care settings, particularly in our primary care centers where approximately 79.6% of our health care workers are female according to data provided by our

Human Resources department in November 2023. This gender imbalance limits the generalizability of our findings across all genders. Future research should aim to include a more balanced gender distribution when possible, exploring if VR educational programs have differential effects on various demographic groups. Fourth, the sample size, which is appropriate for a preliminary exploration into VR-based interventions, is nonetheless insufficient for establishing definitive efficacy, underscoring the need for larger more representative studies. Resource-related phased implementation may have introduced variability in delivery, which was mitigated in later stages but could have affected initial participant experience. Future studies should increase the sample size to provide more robust evidence of efficacy. It is also recommended to standardize the implementation process across all phases to minimize variability and improve the reliability of the results.

Conclusions

This pilot study provides initial indications that an 8-week VR-based educational program may positively influence burnout and work engagement among health care professionals. Our findings suggest a reduction in burnout symptoms, as measured by the MBI, and an increase in work engagement, as indicated by the UWES. While the data hint at VR's promise for reducing burnout symptoms and fostering work engagement, the results should be viewed as preliminary. The interpretive value of the findings is limited by the sample size and the absence of a control group, despite the application of rigorous statistical analyses to assess the intervention's impact.

To enhance future assessments and maintain equitable access to potential benefits, subsequent research could adopt a crossover study design. Such a design would involve randomizing participants into initial control and intervention groups, with a subsequent exchange of roles following a predetermined washout period. This methodological approach would allow for a comprehensive evaluation of the VR program's impact by ensuring that each participant acts as their own control, thereby reinforcing the strength of the evidence gathered while ensuring access to the intervention.

This study contributes to the literature on the use of VR technology in education and health care, highlighting the potential of digital health interventions in disease prevention and health promotion, and emphasizing the importance of prioritizing the well-being of health care professionals as a main requirement for the survival of the health care system.

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In refining the format and clarity of our manuscript, we used artificial intelligence–based tools for text editing assistance. It is important to note that these tools were used solely for improving the presentation of our content, with all original ideation and content creation carried out by the human authors. Every artificial intelligence–assisted edit was subject to thorough review and final adaptation by our team to ensure accuracy and integrity of the manuscript.

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Data Availability

The data sets generated or analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions

JFC led the development of the study's software, provided technical support for the virtual reality sessions, was responsible for the data curation and project administration, drafted the initial manuscript, and supervised all data collection phases. NM co-conceptualized the study, developed the study's theoretical framework, was responsible for the audio creation for the sessions, and reviewed and edited the manuscript. CGM, LJCH, and FRCC contributed to the supervision of the sessions and participated in data collection, ensuring the integrity of the data collection process. MJC conducted the formal analysis, played a significant role in interpreting the data, and was a major contributor in writing and revising the manuscript. All authors reviewed and approved the final manuscript for submission and participated in the supervision of the sessions, ensuring rigorous oversight throughout the study.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Mean scores of the Maslach Burnout Inventory and Utrecht Work Engagement Scale.

[[PDF File \(Adobe PDF File\), 94 KB - xr_v1ile55678_app1.pdf](#)]

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Abbreviations

MBI: Maslach Burnout Inventory

UWES: Utrecht Work Engagement Scale

VR: virtual reality

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Original Paper

Perspectives of Medical Students and Developers Regarding Virtual Reality, Augmented Reality, Mixed Reality, and 3D Printing Technologies: Survey Study

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Abstract

Background: Emerging technologies, such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and 3D printing (3DP), have transformative potential in education and health care. However, complete integration has not yet been achieved, and routine use is limited. There may exist gaps in the perspectives of these technologies between users and developers, and improvement may be necessary in developing such technologies.

Objective: The purpose of this study was to investigate the gaps in perspectives between medical students and developers in medical education regarding satisfaction and anticipated future use of VR, AR, MR, and 3DP technologies, as well as developers' perspectives on their advantages and current challenges.

Methods: This retrospective survey study was conducted during a 4-hour elective course over a period of 4 weeks. In this course, computed tomography scans of congenital heart disease patients, medical image processing software, head-mounted displays, and a virtual table were used. Student pre- and postsurveys and the developer survey included demographic and other characteristics, satisfaction, and anticipated future use of VR, AR, MR, and 3DP technologies. The advantages and current challenges of these technologies were only assessed in the developer survey.

Results: The study enrolled 41 participants, including 15 first-year medical students and 26 software and content developers. Students were more satisfied than developers across AR, VR, and 3DP in terms of overall satisfaction (VR and AR: $P < .001$; 3DP: $P = .002$), esthetics (VR: all $P < .001$; AR: vividness, $P = .006$ and design, $P < .001$; 3DP: vividness, $P = .001$ and design, $P = .002$), and continuous use intention (VR: repetition, $P = .04$ and continuous use, $P = .02$). Particularly in VR, satisfaction with reality was higher among students than among developers (real world, $P = .006$). Developers anticipated future use of MR for educating medical students and residents, individual and collaborative surgical planning, and performing surgery on patients. In contrast, students anticipated future use of VR primarily for student education, 3DP for resident education and individual surgical planning, and AR for collaborative surgical planning and performing surgery on patients. Developers perceived the inherent capabilities of VR, AR, and MR technologies as strengths, with hardware performance identified as a drawback. For 3DP, the possibility of customized product manufacturing was seen as an advantage, while cost was seen as a disadvantage.

Conclusions: This study elucidated the different perspectives between medical students and developers regarding 3D technologies, highlighting the discrepancy in potential applications and challenges within the medical field. These findings will guide the integration of 3D technologies in education and health care to fulfill the needs and goals of both medical students and developers.

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KEYWORDS

medical student; developer; virtual reality; augmented reality; mixed reality; 3D printing; perspective; survey

Introduction

Background

In recent years, 3D technologies, including virtual reality (VR), augmented reality (AR), mixed reality (MR), and 3D printing (3DP), have shown considerable potential to revolutionize the fields of education and health care [1-3]. Each of these technologies offers different capabilities. The basic principle of VR involves the immersion of users in artificial environments, providing complete immersion and removing them from their immediate surroundings [4]. On the other hand, the principle of AR involves overlaying digital information onto the real world, allowing interaction between the physical and digital realms [5]. MR goes a step further by merging tangible and virtual worlds [6]. Unlike VR, which fully immerses the user in a virtual environment, and AR, which overlays digital information onto the physical world, MR is defined as a technology that seamlessly merges the physical world with the virtual world, allowing physical and digital objects to coexist and interact in real time [7]. In MR, virtual objects appear to exist in the same space as physical objects, and users can interact with both in a natural and intuitive way. These technologies are commonly experienced using headsets, allowing hands-free viewing of digital information within the user's view. Additionally, 3DP is a method of creating a 3D object layer by layer from a computer-generated design [5]. Beyond these basic principles, these technologies have become powerful tools in facilitating practical training and skill development. Numerous studies have highlighted the importance of integrating these cutting-edge technologies into medical and surgical education [8-10].

VR is versatile with applications in 3D anatomical models, surgical planning, and medical skills practice simulators [11]. It has been actively evaluated for its efficacy in anatomy education and has been often compared with traditional methods like dissection and lectures, as well as modern techniques like 2D images and blended instructions [12,13]. In surgical education, VR can effectively address challenges, such as the shortage of available mentors, optimization of training time, and mitigation of the complexities associated with operative procedures [14]. Additionally, by replicating complex surgical scenarios in a controlled and risk-free environment, VR offers a safe space for trainees to enhance their skills and decision-making processes.

AR has been incorporated into different phases of medical training, and it serves as an essential tool for anatomical instruction, which can assist students during classroom studies, a tool in image-based training simulators, and an interactive platform to improve clinical skills [15]. The integration of AR has revolutionized medical education by providing students with real-time visualizations of complex anatomical structures and creating interactive and immersive learning experiences that deepen their understanding of medical concepts [16]. In addition, AR-based training simulators enable learners to

improve their practical skills and confidence by allowing them to practice medical procedures in a simulated digital environment before performing them in clinical settings [17]. There is a key difference between AR-based training simulators and VR-based training simulators. VR-based training simulators simulate the actual workspace within a 3D modeling environment and involve the handling of virtual objects using controllers. However, AR-based training simulators allow users to interact with digital elements while still being aware of their physical surroundings [18]. This allows for a more seamless integration of virtual elements with real-world objects and scenarios, offering unique training opportunities that VR alone may not be able to provide.

MR has rapidly advanced in recent years, establishing itself as a fundamental research direction within the field of intelligent medicine. There are significant numbers of MR applications in surgical training and planning [19,20]. Previous studies have found that by expanding upon conventional computer-assisted surgical techniques, MR offers significant potential for enhancing orthopedic training and needle insertion skills [3,21]. This transformative impact extends beyond the confines of surgical applications, encompassing the sphere of medical education as a whole. Some pioneering research has demonstrated that MR has the potential to enhance the efficacy of conveying intricate content through remote learning, a modality that remains pivotal in the field of education [22].

3DP provides a tangible and immersive approach to medical and surgical education [23]. 3DP enables the production of objects with very intricate details and offers the versatility to print a model with different materials, including hydrogels, thermoplastics and thermosets, metals, and ceramics [2,24]. In addition, personalized patient-specific 3DP models help students understand variation and pathology, while surgical planning benefits from accurate organ replicas that enhance visualization and reduce errors [25]. Trainees train their hands-on skills on 3D-printed models in a risk-free environment, and educators simulate complex cases for better decision-making [26]. Furthermore, 3DP plays a crucial role in advancing medical research by facilitating the prototyping of medical innovations, including devices and implants, thus shaping the future of the field [27,28].

These technologies have been well developed in recent years, and this is reflected in a variety of medical specialties in medical education and health care. While these technologies have been widely used to complement existing methods, they are increasingly becoming integral tools, particularly in settings where conventional approaches face limitations or challenges. In educational settings that have constraints, such as limited access to cadavers, high costs, concerns about formaldehyde exposure, ethical considerations, and challenges posed by pandemics, these technologies have gradually replaced traditional methods for medical students [29,30]. Similarly, in health care, personalized instruments, along with advancements like bone grafting and customized implants, are replacing

traditional approaches [31]. As they continue to complement and replace traditional methods, they offer innovative solutions to address various challenges and constraints encountered in both education and health care.

In South Korea, after students are accepted into medical school, they typically spend 2 years in premedical education. During this premedical education, they study basic subjects, such as basic sciences, and other fundamental subjects essential for their medical studies. Therefore, the first year of medical school is an appropriate time to introduce these latest technologies. Because students have already established a solid foundation in basic sciences during their premedical education, they are better equipped to grasp the complexities of these technologies and integrate them into their medical education effectively. The current technology curriculum is situated in the context following the completion of the anatomy course and preceding the commencement of the clinical curriculum. Prior to enrolling in this technology curriculum at Seoul National University College of Medicine, students are exposed to heart content in their human anatomy course using these tools. A survey comparing student evaluation of the same content through traditional education versus the use of these tools revealed that the tools were considerably helpful [32].

Theoretical Background

While numerous studies have examined the satisfaction and effectiveness among medical students, residents, and fellows [33-36], complete integration into routine education and health care has not been achieved. These studies have primarily focused on users, with little attention given to the perspectives of developers, who are responsible for creating these technologies. Consequently, the findings offer an incomplete picture. As these technologies continue to evolve in medical education, it becomes essential to understand the perspectives of both medical students and developers regarding the technologies.

Relationship Between Users and Developers

Users and developers are commonly considered 2 distinct groups of people [37]. Due to differences in backgrounds and situations, developers and users often share different and sometimes conflicting interests during the software development process. The root cause of many issues is perceived to be ongoing cultural differences. Other theories suggest that personality differences or even differences in how users and developers think cause these barriers [38]. Developers tend to be achievement-oriented and are intrinsically motivated to develop excellent software, while users are primarily focused on improving efficiency and solving problems [39]. The potential conflict of interest between them can negatively affect the performance of software development. Therefore, a study is needed to understand the gaps in their perspectives regarding the range of tools and techniques, which might support future development. Understanding their perspectives might help in refining the implementation strategies of these technologies in the large scope of curriculum development.

User and Developer Satisfaction and System Success

User satisfaction is one of the most frequently cited factors for measuring system success and one of the most difficult factors to measure [40]. A great deal of research has been conducted to understand the notion of user satisfaction. User satisfaction, as defined by previous researchers, encompasses meeting user needs [41], positive cognitive responses to system use [42], and measurable effects in projects [43]. In education, satisfaction plays a crucial role as a barrier to continuous use and adoption of these technologies [44]. While people may use various technologies without being fully satisfied with them, in the context of education, satisfaction impacts the effectiveness of learning experiences [45]. Students who are dissatisfied with the technologies used in their education may experience hindered engagement, motivation, and, ultimately, compromised learning outcomes [46]. High satisfaction with technology not only correlates with actual experiences of the technology but also enables individuals to anticipate which technologies may be beneficial in future situations. In addition, considering that developers not only represent the core of the development process but also account for the largest cost in software development, it is necessary to investigate developer satisfaction. Ultimately, developer satisfaction is essential for system development success.

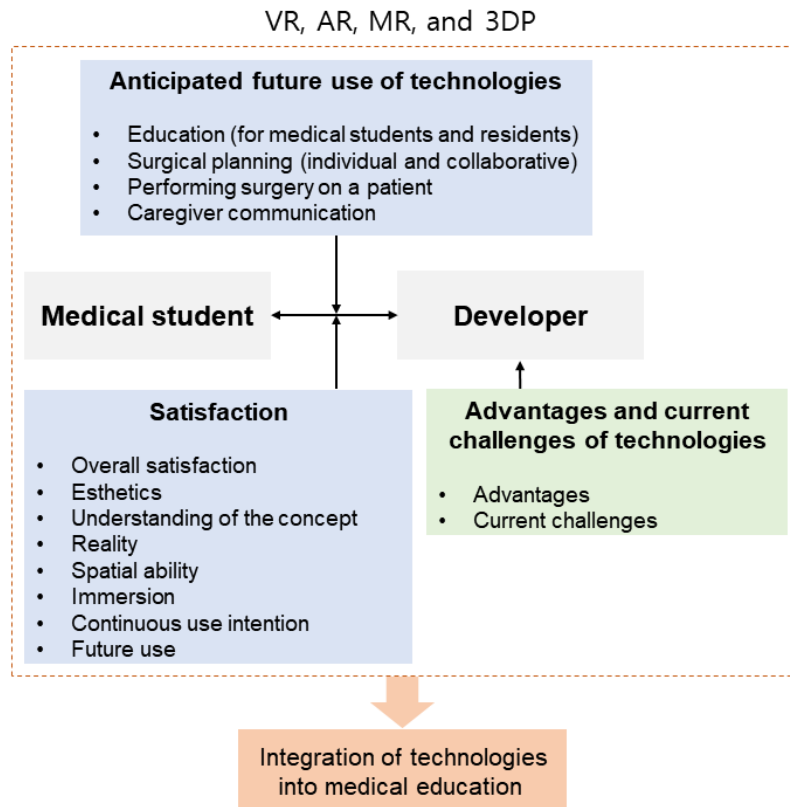
User and Developer Anticipations Regarding Technology

Anticipations of future use in technological development are more than simply descriptions of future products and systems. These anticipations can change the application process of novel technology in medical education as they guide the actions of technology developers [47]. At the same time, extrapolating future technology from past developments can narrow down the potential paths of technological advancement [48]. However, users play a role in shaping the future of technology, as the shape of technology depends on their anticipations of use [47]. To conclude, it is important to consider anticipations for investigating the gap in medical education. We suggest viewing envisaged sociotechnical futures as negotiation arenas between the present and the imagined futures. There is a lack of knowledge on differences in user and developer anticipations regarding the types of technologies that are likely to be widely used in different scenarios. In medical education, there may remain a gap in the anticipated use of these technologies between medical students and developers, and it may be needed to figure out the differences in anticipations to effectively bridge this gap.

Conceptual Framework

This study hypothesized a conceptual framework (Figure 1) in which there is a gap between medical students and developers in terms of satisfaction and anticipated future use of VR, AR, MR, and 3DP technologies, and this gap is associated with the complete integration into medical education. Additionally, from a technological perspective, this study hypothesized that factors related to the advantages and current challenges associated with these technologies from the developers' perspectives could potentially delay the integration of medical education.

Figure 1. Conceptual framework of this study. 3DP: 3D printing; AR: augmented reality; MR: mixed reality; VR: virtual reality.



Study Questions

The aim of this study was to investigate the gap in perspectives between medical students and developers regarding the satisfaction and anticipated future use of VR, AR, MR, and 3DP technologies, as well as developers' perspectives on their advantages and current challenges. The following specific research questions guided this study:

1. What is the difference in satisfaction levels with VR, AR, MR, and 3DP between medical students and developers?
2. What differences exist in the anticipated future use of VR, AR, MR, and 3DP between medical students and developers?
3. What are the developers' perceptions of the advantages and current challenges associated with VR, AR, MR, and 3DP?

Methods

Participants

All participants voluntarily enrolled in an elective course on 3D imaging software and the applications of 3D technology for human anatomy at Seoul National University College of Medicine, Seoul, Republic of Korea, and were voluntarily recruited. In the academic year 2023, 15 first-year medical students and 26 software and content developers with expertise in VR, AR, or 3DP participated in this study.

Curriculum and Study Design

The course and the surveys were designed for educational quality improvement purposes prospectively before actual application of the curriculum. The statistical research was

performed retrospectively after the completion of the curriculum.

Contents and Schedule for the Elective Course

The elective course spanned 4 weeks with 4 sessions, each lasting 4 hours (Table 1). A graphical diagram of the elective course and a workflow diagram detailing the hands-on practice are shown in Figures 2 and 3. During the initial 3 weeks, the curriculum included lectures and hands-on sessions focusing on the application of artificial intelligence (AI) technology in medical imaging. The AI-based image processing software quickly and automatically segmented the anatomical structures, allowing for adequate processing within the first 3 weeks. Only the finer anatomical structures required separate segmentation. The students were divided into 4 groups and used medical image processing software to outline anatomical structures. In this study, heart models were selected owing to complex 3D relationships between components within the thoracic cavity. These heart models were personalized and customized to match the anatomical structure of each patient with congenital heart disease (CHD). The process of creating a 3D reconstruction from a patient's computed tomography scan is shown in Multimedia Appendix 1. The 3D segmented models were constructed for an interrupted aortic arch (Multimedia Appendix 2), Ebstein anomaly (Multimedia Appendix 3), transposition of the great arteries (Multimedia Appendix 4), and major aortopulmonary collateral arteries (Multimedia Appendix 5). The segmented and processed images were then integrated into various tools: VR via Oculus Quest 2 (Meta), AR via HoloLens 2 (Microsoft Corp), and 3DP for physical modeling. In the final week, students presented on the future of medical education and clinical environments, drawing upon tools from the first 3

weeks of the course. In the curriculum management process, faculty members specializing in anatomy education oversaw the development of these tools and modalities. In addition, the course in which these tools were introduced was typically taught

by not only anatomy experts, who use these technologies effectively in anatomy education, but also software developers. Content developers in the course worked with students to create CHD content.

Table 1. Table of contents and schedule for the elective course at Seoul National University College of Medicine, 2023.

| Week and time | Topic | Detailed content | Teaching method |
|---|--|---|-------------------------------|
| Week 1: Medical image-based AI^a technology (n=5) | | | |
| 1:00-1:10 PM | Presurvey for students | • N/A ^b | Survey |
| 1:10-2:00 PM | Understanding medical image-based AI technology | • N/A | Lecture |
| 2:00-2:10 PM | Rest | • N/A | N/A |
| 2:10-2:30 PM | Use of AI technology in medical imaging; 3DP ^c | • N/A | Lecture |
| 2:30-2:40 PM | Rest | • N/A | N/A |
| 2:40-3:00 PM | Use of AI technology in medical imaging; VR ^d , AR ^e , and MR ^f | • N/A | Lecture |
| 3:00-3:10 PM | Rest | • N/A | N/A |
| 3:10-4:50 PM | Learning the functions of medical image processing software | • N/A | Lecture and hands-on practice |
| 4:50-5:00 PM | Course wrap-up | • N/A | N/A |
| Week 2: AI segmentation using medical image processing software (n=15; 4 groups) | | | |
| 1:00-1:50 PM | AI segmentation using medical image processing software | • AI segmentation on cases of CHD ^g patients, including IAA ^h , Ebstein anomaly, TGA ⁱ , and MAPCA ^j | Hands-on practice |
| 1:50-2:00 PM | Rest | • N/A | N/A |
| 2:00-2:50 PM | AI segmentation using medical image processing software | • AI segmentation on the abovementioned cases | Hands-on practice |
| 2:50-3:00 PM | Rest | • N/A | N/A |
| 3:00-3:50 PM | AI segmentation using medical image processing software | • AI segmentation on the abovementioned cases | Hands-on practice |
| 3:50-4:00 PM | Rest | • N/A | N/A |
| 4:00-4:50 PM | AI segmentation using medical image processing software | • AI segmentation on the abovementioned cases | Hands-on practice |
| 4:50-5:00 PM | Course wrap-up | • N/A | N/A |
| Week 3: VR, AR, and 3DP experience (n=15; 4 groups) | | | |
| 1:00-4:30 PM | VR experience | <ul style="list-style-type: none"> • Anatomy structures • Pediatric CHD model, including IAA, Ebstein anomaly, TGA, and MAPCA (patient-specific model) • Digestive process • Respiratory process • Muscle movement | Group rotation experience |
| 1:00-4:30 PM | AR experience | <ul style="list-style-type: none"> • Pediatric CHD model, including IAA, Ebstein anomaly, TGA, and MAPCA (patient-specific model) • Kidney cancer model • Brain tumor model | Group rotation experience |

| Week and time | Topic | Detailed content | Teaching method |
|--|--|--|-----------------------------|
| 1:00-4:30 PM | 3DP experience | <ul style="list-style-type: none"> Pediatric CHD model, including IAA, Ebstein anomaly, TGA, and MAPCA (patient-specific model) Simulator model for surgery training | Group rotation experience |
| 1:00-4:30 PM | 3DP lab tour | <ul style="list-style-type: none"> 3DP lab Production process lab | Group rotation experience |
| 4:30-4:50 PM | Rest | <ul style="list-style-type: none"> N/A | N/A |
| 4:50-5:00 PM | Course wrap-up | <ul style="list-style-type: none"> N/A | N/A |
| Week 4: Presentation (n=15; 4 groups) | | | |
| 1:00-1:30 PM | Group 1: Presentation and discussion | <ul style="list-style-type: none"> N/A | Presentation and discussion |
| 1:30-1:40 PM | Rest | <ul style="list-style-type: none"> N/A | N/A |
| 1:40-2:10 PM | Group 2: Presentation and discussion | <ul style="list-style-type: none"> N/A | Presentation and discussion |
| 2:10-2:20 PM | Rest | <ul style="list-style-type: none"> N/A | N/A |
| 2:20-2:50 PM | Group 3: Presentation and discussion | <ul style="list-style-type: none"> N/A | Presentation and discussion |
| 2:50-3:00 PM | Rest | <ul style="list-style-type: none"> N/A | N/A |
| 3:00-3:30 PM | Group 4: Presentation and discussion | <ul style="list-style-type: none"> N/A | Presentation and discussion |
| 3:30-4:00 PM | Rest | <ul style="list-style-type: none"> N/A | N/A |
| 4:00-4:20 PM | Postsurvey for students and developers | <ul style="list-style-type: none"> N/A | Survey |
| 4:20-4:40 PM | Group photo | <ul style="list-style-type: none"> N/A | N/A |
| 4:40-5:00 PM | Course wrap-up | <ul style="list-style-type: none"> N/A | N/A |

^aAI: artificial intelligence.

^bN/A: not applicable.

^c3DP: 3D printing.

^dVR: virtual reality.

^eAR: augmented reality.

^fMR: mixed reality.

^gCHD: congenital heart disease.

^hIAA: interrupted aortic arch.

ⁱTGA: transposition of the great arteries.

^jMAPCA: major aortopulmonary collateral arteries.

Figure 2. Graphical diagram of the elective course. 3DP: 3D printing; AR: augmented reality; MR: mixed reality; VR: virtual reality.

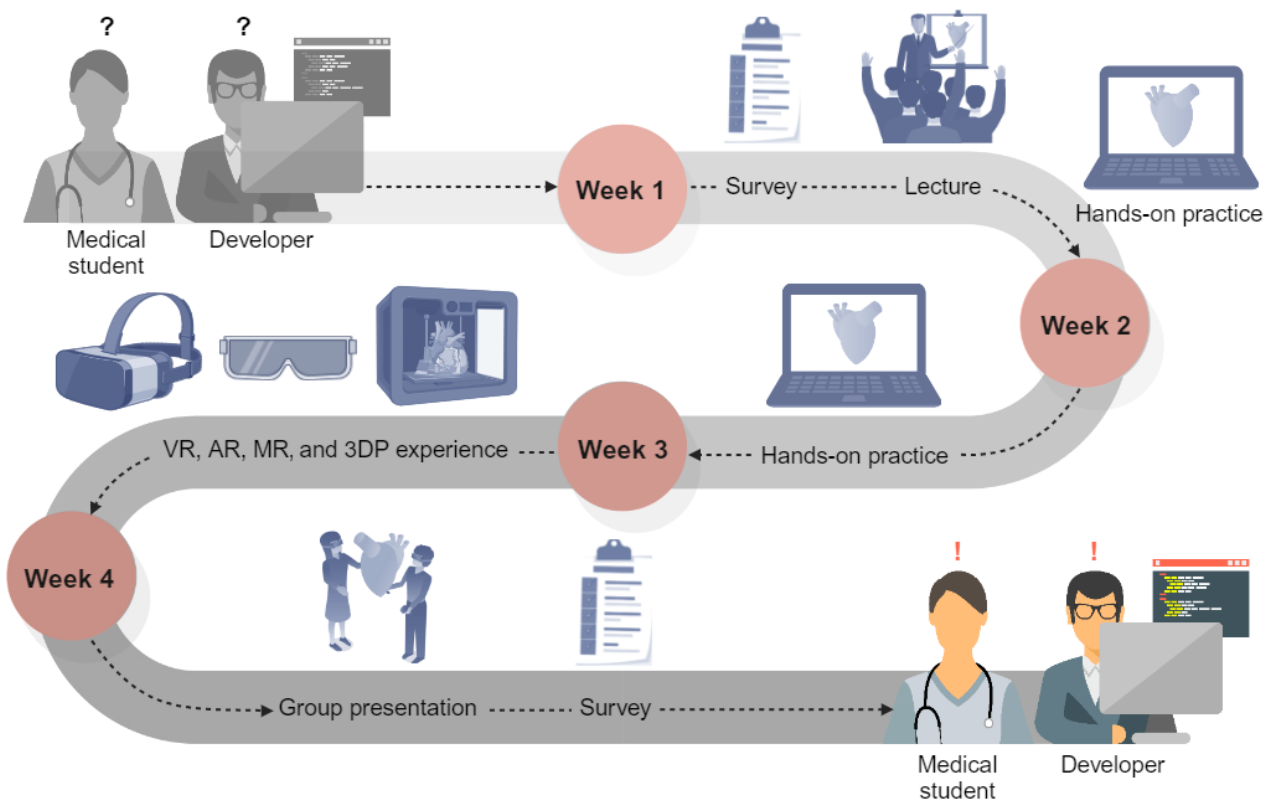
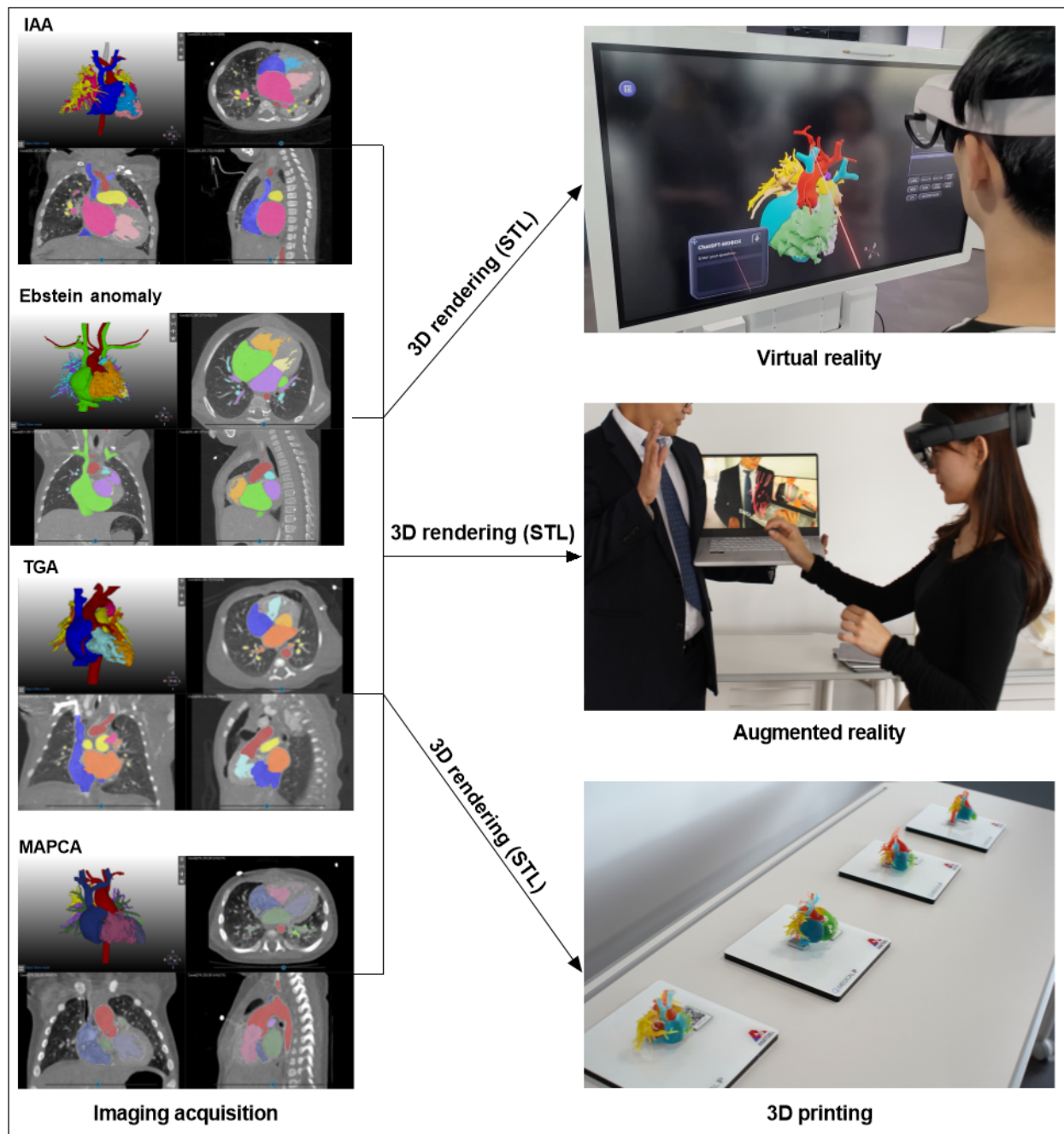


Figure 3. Workflow diagram of hands-on practice for the elective course. Segmented and refined 3D congenital heart disease models are used for not only virtual and augmented reality but also 3D printing. IAA: interrupted aortic arch; MAPCA: major aortopulmonary collateral arteries; STL: standard tessellation language; TGA: transposition of the great arteries.



Devices and Software

This study employed a virtual dissection table (MDBOX, MEDICAL IP Co, Ltd), a VR headset (Oculus Quest 2), an AR headset (HoloLens 2), and medical image processing software (MEDIP PRO, MEDICAL IP Co, Ltd).

Student Pre- and Postsurveys

The students' survey consisted of pre- and postsurveys. The presurvey included questions about demographic information and prior experience with 3D medical technologies. The majority of previous studies used 5-point Likert scale-based questionnaires to assess user satisfaction, device usability,

perceived engagement, and the influence on anatomy education [49]. Therefore, in the postsurvey, students used a 5-point Likert-type scale to indicate their overall satisfaction and satisfaction levels with VR, AR, and 3DP across 7 categories, which were organized into 2 subscales each ([Multimedia Appendix 6](#)). The 7 categories included esthetics, understanding of the concept, reality, spatial ability, immersion, continuous use intention, and future use. The use of new technologies in education is considered to be about experiences that include esthetic enjoyment as well [50]. Moreover, well-designed and esthetically pleasing content is more likely to engage users and improve their overall experience [51]. Clarity and comprehensibility of the content are crucial for users to

effectively grasp concepts. 3D models provide users with the flexibility to explore structures from desired angles, thereby facilitating deeper comprehension and learning [52]. In education, aspects of spatial ability can be enhanced through experience, suggesting the potential for facilitating users' learning of 3D structures [53]. Previous studies have found a correlation between spatial abilities and assessment of anatomy knowledge, with spatial training being shown to improve spatial abilities [54]. In these technology-rich educational environments, immersion has been identified as one of the primary drivers of student learning [55]. Continuous use intention is an important factor for the successful adoption of technology [56]. Additionally, satisfaction with technologies expected to be used in clinical areas or their potential for substitution was also investigated. To further explore students' thoughts and insights through their presentations, students were asked questions about their expectations regarding the use of these technologies in various situational scenarios in the future. These questionnaires were prepared using Google Forms (Google LLC).

Developer Survey

The developers took a single survey, which included demographic information, department affiliation, and years of professional experience. Similar to the student postsurvey, developers rated their overall satisfaction and satisfaction levels with VR, AR, and 3DP using a 5-point Likert-type scale across the same 7 categories organized into 2 subscales each. The survey also inquired about their expectations regarding the integration of these technologies into various medical settings within 5 years. Furthermore, the survey included questions exploring only developers' perspectives on the advantages and challenges of VR, AR, MR, and 3DP. These questionnaires were prepared using Google Forms (Google LLC).

Statistical Analysis

Statistical analyses were performed using SPSS software, version 26 (IBM Corp) and Prism, version 9 (GraphPad). Differences in satisfaction levels between students and developers for VR, AR, and 3DP were assessed using independent *t* tests. Statistical significance was determined at $P < .05$. Owing to the possibility of a type I (false positive) error resulting from the multiple comparison analyses, we applied Bonferroni correction. After Bonferroni correction, most

of the associations were not considered significant, with the adjusted significance level set at $P < .003$.

Ethical Considerations

This study was approved by the Institutional Review Board of Seoul National University College of Medicine (E-2307-030-1447). The study was entirely retrospective (using existing student and developer surveys), and the requirement for informed consent was waived.

Results

Participants

In this survey study, we recruited 15 first-year medical students and 26 software and content developers who participated in a 4-week elective course that combined lectures and hands-on sessions. The data collection started on May 22, 2023, and ended on June 19, 2023.

Demographic and Other Characteristics of Medical Students

The demographic and other characteristics of the 15 medical students are provided in Table 2. Their mean age was 21.5 (SD 1.5) years, and there were 12 (80%) male students and 3 (20%) female students. All students were familiar with VR, and 14 (93%) students were aware of AR and MR. However, 14 (93%) students had difficulty distinguishing between these technologies. Regarding VR content, 11 (73%) students engaged with it 1-3 times a month, with 8 (73%) engaging for educational purposes and 5 (46%) engaging for gaming. AR content was less frequent, with 5 (33%) students experiencing it 1-2 times a year, mainly in gaming (4/5, 80%) and education (2/5, 40%). 3DP content was used 1-2 times a year for educational purposes by 9 (60%) students. Moreover, 11 (73%) students used VR-based medical content, with 6 (55%) students focusing on heart-related content (heart VR education was previously provided in the anatomy curriculum) and 5 (46%) using unknown content. None had prior experience with AR-based medical content, but 2 (13%) students had experience with 3DP-based medical content. Of these 2 students, 1 (50%) used a pediatric cardiac model and 1 (50%) used content of unknown nature.

Table 2. Demographic and other characteristics of medical students (n=15).

| Characteristic | Value |
|---|------------|
| Age (years), mean (SD) | 21.5 (1.5) |
| Gender, n (%) | |
| Male | 12 (80) |
| Female | 3 (20) |
| Please select all the options you have heard of among VR^a, AR^b, MR^c, and 3DP^d, n (%) | |
| VR | 15 (100) |
| AR | 14 (93) |
| MR | 14 (93) |
| Can you distinguish between VR, AR, and MR? n (%) | |
| No | 14 (93) |
| Yes | 1 (7) |
| Have you ever experienced VR content? n (%) | |
| No | 4 (27) |
| Yes | 11 (73) |
| If you have experienced VR content, how often did you experience it?^e, n (%) | |
| Everyday | 0 (0) |
| 3-4 times a week | 0 (0) |
| 1-2 times a week | 0 (0) |
| 1-3 times a month | 11 (100) |
| 1-2 times a year | 0 (0) |
| If you have experienced VR content, please select all the experiences you had^e, n (%) | |
| Game | 5 (46) |
| Travel | 0 (0) |
| Movies or television shows | 0 (0) |
| Music (eg, concerts and music videos) | 0 (0) |
| Education | 8 (73) |
| Art galleries | 0 (0) |
| Have you ever experienced AR content? n (%) | |
| No | 10 (67) |
| Yes | 5 (33) |
| If you have experienced AR content, how often did you experience it?^e, n (%) | |
| Everyday | 0 (0) |
| 3-4 times a week | 0 (0) |
| 1-2 times a week | 0 (0) |
| 1-3 times a month | 0 (0) |
| 1-2 times a year | 5 (100) |
| If you have experienced AR content, please select all the experiences you had^e, n (%) | |
| Game | 4 (80) |
| Travel | 0 (0) |
| Movies or television shows | 0 (0) |
| Music (eg, concerts and music videos) | 0 (0) |

| Characteristic | Value |
|--|----------|
| Education | 2 (40) |
| Art galleries | 0 (0) |
| Have you ever experienced 3DP content? n (%) | |
| No | 6 (40) |
| Yes | 9 (60) |
| If you have experienced 3DP content, how often did you experience it?^e, n (%) | |
| Everyday | 0 (0) |
| 3-4 times a week | 0 (0) |
| 1-2 times a week | 0 (0) |
| 1-3 times a month | 0 (0) |
| 1-2 times a year | 9 (100) |
| If you have experienced 3DP content, please select all the experiences you had^e, n (%) | |
| Game | 0 (0) |
| Travel | 0 (0) |
| Movies or television shows | 0 (0) |
| Music (eg, concerts and music videos) | 0 (0) |
| Education | 9 (100) |
| Art galleries | 0 (0) |
| Have you ever experienced VR-based medical content? n (%) | |
| No | 4 (27) |
| Yes | 11 (73) |
| If you have experienced VR-based medical content, what is the name of the content? (If unknown, please write "unknown")^e, n (%) | |
| Heart | 6 (55) |
| Unknown | 5 (46) |
| Have you ever experienced AR-based medical content? n (%) | |
| No | 15 (100) |
| Yes | 0 (0) |
| Have you ever experienced 3DP-based medical content? n (%) | |
| No | 13 (87) |
| Yes | 2 (13) |
| If you have experienced 3DP-based medical content, what is the name of the content? (If unknown, please write "unknown")^e, n (%) | |
| Pediatric cardiac model | 1 (50) |
| Unknown | 1 (50) |

^aVR: virtual reality.

^bAR: augmented reality.

^cMR: mixed reality.

^d3DP: 3D printing.

^eOnly the subgroup of students who experienced either VR, AR, or 3DP.

Demographic and Other Characteristics of Developers

The demographic and other characteristics of the 26 developers are shown in Table 3. Their mean age was 28.2 (SD 4.5) years,

and there were 7 (27%) male developers and 19 (73%) female developers. There was no bias in their expertise. The developers were individuals with backgrounds in software and content development and had various degrees and majors (Multimedia

Appendix 7). Among the 26 developers, 15 (58%) were associated with VR, 4 (15%) with AR, and 10 (39%) with 3DP. Regarding their years of professional experience, most developers had 1 year of experience (9/26, 35%), followed by

less than 1 year of experience (4/26, 15%); 4 and 5 years of experience (each 3/26, 12%); 2, 3, and 8 years of experience (each 2/26, 8%); and 7 years of experience (1/26, 4%).

Table 3. Demographic and other characteristics of developers (n=26).

| Characteristic | Value |
|---|------------|
| Age (years), mean (SD) | 28.2 (4.5) |
| Gender, n (%) | |
| Male | 7 (27) |
| Female | 19 (73) |
| Which departments are you affiliated with? n (%) | |
| VR ^a | 15 (58) |
| AR ^b | 4 (15) |
| 3DP ^c | 10 (39) |
| How many years of experience do you have? n (%) | |
| No experience | 0 (0) |
| Less than 1 year | 4 (15) |
| 1 year | 9 (35) |
| 2 years | 2 (8) |
| 3 years | 2 (8) |
| 4 years | 3 (12) |
| 5 years | 3 (12) |
| 6 years | 0 (0) |
| 7 years | 1 (4) |
| 8 years | 2 (8) |
| 9 years | 0 (0) |
| More than 10 years | 0 (0) |

^aVR: virtual reality.

^bAR: augmented reality.

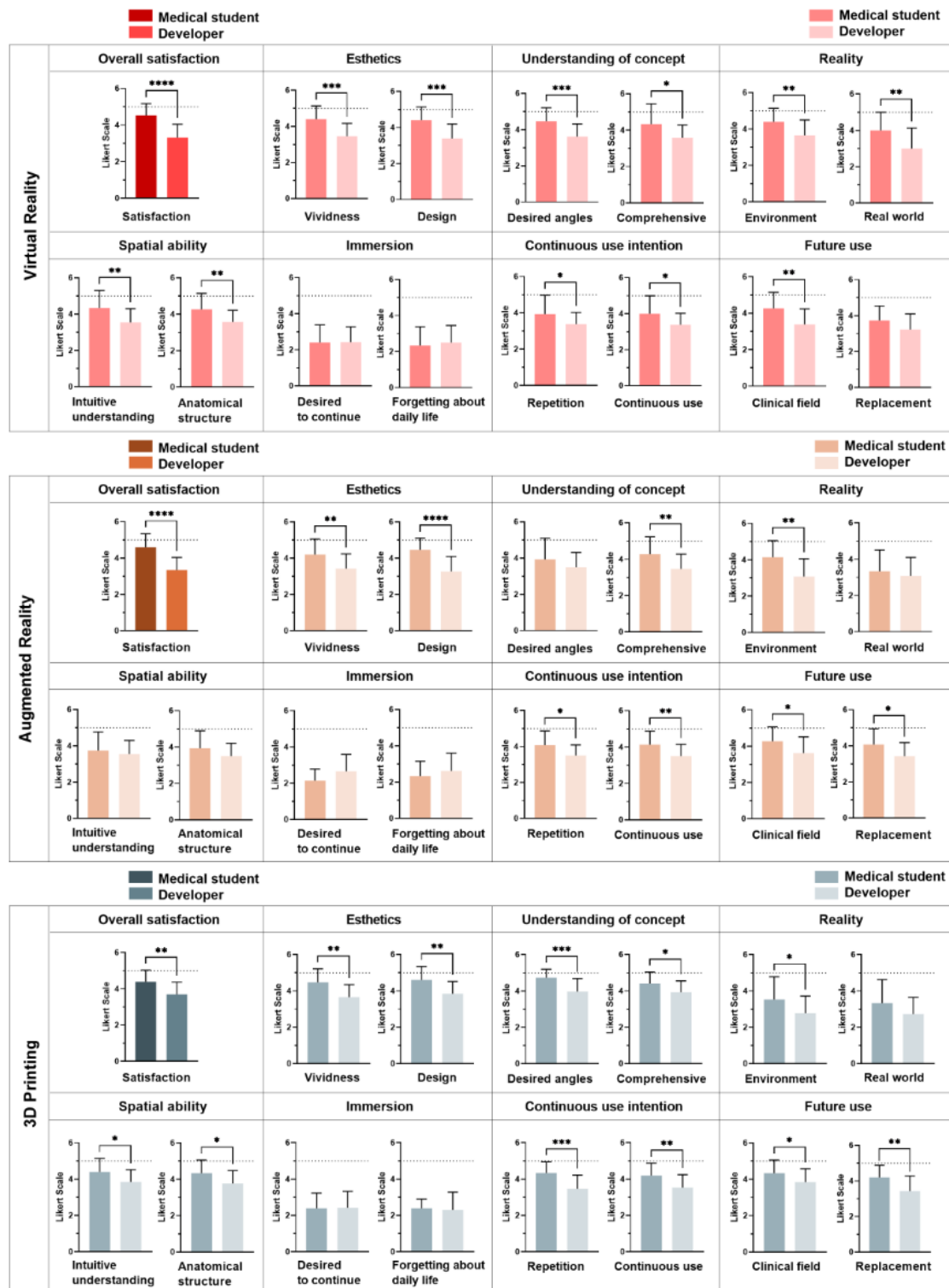
^c3DP: 3D printing.

Levels of Satisfaction With VR, AR, and 3DP Between Medical Students and Developers

Levels of satisfaction with VR, AR, and 3DP among medical students and developers are shown in Figure 4 and Tables S1-S3 in Multimedia Appendix 8. The satisfaction results are presented in terms of overall satisfaction and the following 7 categories: esthetics, understanding of the concept, reality, spatial ability, immersion, continuous intention, and future use. Specifically, 2 questions were included in each category. In terms of esthetics, the vividness and design of the content were considered. For understanding of the concept, questions assessed how easily

participants understood the content and if they were able to learn effectively. Reality focused on whether participants felt a sense of realism within the content and its surroundings. Spatial ability questions evaluated participants' satisfaction to intuitively grasp the structures and understand the relationships between different structures. Continuous use intention investigated participants' desire to repeatedly engage with the content and continue its use. Future use included specific inquiries about the potential application of these technologies in clinical settings and their potential to replace conventional methods.

Figure 4. Medical students' (n=15) and developers' (n=26) levels of satisfaction with virtual reality, augmented reality, and 3D printing have been ranked on a 5-point Likert-type scale (1=very dissatisfied to 5=very satisfied). Participants were asked about their overall satisfaction with virtual reality, augmented reality, and 3D printing, as well as their satisfaction with 7 categories organized into 2 subscales. * $P<.05$, ** $P<.01$, *** $P<.001$, **** $P<.0001$.



Overall satisfaction with VR, AR, and 3DP was significantly higher among students than among developers. There was no significant difference in satisfaction with immersion in VR, AR, and 3DP between medical students and developers. In the case of VR (Figure 4 and Table S1 in Multimedia Appendix 8), the satisfaction levels of students were significantly higher than those of developers in esthetics (vividness: 4.52 vs 3.31; design:

4.40 vs 3.38), understanding of the concept (desired angles: 4.47 vs 3.62; comprehensive: 4.33 vs 3.58), reality (environment: 4.40 vs 3.65; real world: 4.00 vs 3.00), spatial ability (intuitive understanding: 4.33 vs 3.54; spatial perception: 4.27 vs 3.58), continuous use intention (repetition: 3.93 vs 3.39; continuous use: 4.00 vs 3.39), and future use (clinical field: 4.27 vs 3.39). However, after Bonferroni correction to adjust for

multiple variables, only overall satisfaction ($P<.001$), esthetics (vividness and design, $P<.001$), and understanding of the concept (desired angles, $P<.001$) remained statistically significant.

Similarly, in the case of AR (Figure 4 and Table S2 in [Multimedia Appendix 8](#)), the satisfaction levels of students were significantly higher than those of developers in esthetics (vividness: 4.20 vs 3.42; design: 4.47 vs 3.27), understanding of the concept (comprehensive: 4.27 vs 3.46), reality (environment: 4.13 vs 3.08; real world: 4.00 vs 3.00), continuous use intention (repetition: 4.07 vs 3.50; continuous use: 4.13 vs 3.50), and future use (clinical field: 4.27 vs 3.61; replacement: 4.07 vs 3.42). However, after Bonferroni correction to adjust for multiple variables, only overall satisfaction ($P<.001$), esthetics (design, $P<.001$), and reality (environment, $P=.002$) remained statistically significant.

In the case of 3DP (Figure 4 and Table S3 in [Multimedia Appendix 8](#)), the satisfaction levels of students were significantly higher than those of developers in esthetics (vividness: 4.47 vs 3.65; design: 4.60 vs 3.85), understanding of the concept (desired angles: 4.73 vs 3.96; comprehensive: 4.40 vs 3.92), reality (environment: 3.53 vs 2.77), spatial ability (intuitive understanding: 4.40 vs 3.85; spatial perception: 4.33 vs 3.77), continuous use intention (repetition: 4.33 vs 3.46; continuous use: 4.20 vs 3.54), and future use (clinical field: 4.33 vs 3.85; replacement: 4.20 vs 3.42). However, after Bonferroni correction to adjust for multiple variables, only overall satisfaction ($P<.001$), esthetics (vividness, $P=.001$; design, $P=.002$), understanding of the concept (desired angles, $P<.001$), and continuous use intention (repetition, $P<.001$) remained statistically significant.

Anticipations for the Future Use of VR, AR, MR, and 3DP Between Medical Students and Developers

Future usage expectations of VR, AR, MR, and 3DP between medical students and developers are illustrated in [Multimedia Appendix 9](#). Students expected VR and AR to be the most frequently used technologies in medical education (8/15, 53% and 5/15, 33%, respectively), while MR and 3DP were less anticipated. In contrast, 10 (38%) developers predicted MR to be the most widely used technology, followed by 3DP, with VR and AR having low expected use. In educating residents, 7 (47%) students anticipated 3DP to be the most widely used technology, followed by MR, VR, and AR. Moreover, 11 (42%) developers expected MR to be the dominant technology, followed by 3DP, AR, and VR.

For individual surgical planning, 7 (47%) students expected 3DP to be the most widely used technology, followed by VR, AR, and MR. Moreover, 11 (42%) developers anticipated MR to be the most widely used technology, followed by 3DP, VR, and AR. In collaborative surgical planning, 6 (46%) students anticipated AR to be the most widely used technology, followed by MR, VR, and 3DP. Moreover, 12 (46%) developers expected MR to be the dominant technology, followed by 3DP, AR, and VR.

For surgical procedures on patients, 8 (53%) students expected AR to be the most widely used technology, followed by VR,

MR, and 3DP. Moreover, 14 (52%) developers anticipated MR to be the most widely used technology. In explaining medical information to patients' caregivers, 13 (87%) students anticipated 3DP to be the most widely used technology, followed by VR and MR. Moreover, 10 (38%) developers anticipated 3DP to be the most widely used technology, followed by MR, AR, and VR.

Developers' Perceptions of the Advantages and Current Challenges in VR, AR, MR, and 3DP

The developers' views on the advantages and current challenges of VR, AR, MR, and 3DP are presented in [Multimedia Appendix 10](#). Regarding VR, developers highlighted immersion (11/26, 42%) and the expansiveness of space (8/26, 31%) as key advantages. However, none reported providing experiences similar to real environments as a VR advantage. The main challenge was hardware performance (4/26, 31%), followed by a lack of proactive content production, user-friendliness, and pricing and health issues.

Regarding AR, developers considered engagement in AR (11/26, 42%) as its main advantage, followed by recognizing interactivity and appreciating its ability to provide experiences similar to real environments. None of them reported refining information in AR as an advantage. The main challenge was hardware performance (10/26, 38%), followed by user-friendliness, a lack of proactive content production, and issues related to price and health.

Regarding MR, developers highlighted the integration of real and virtual spaces as the primary advantage (13/26, 50%), with 19% (5/26) noting the provision of realistic virtual spaces. Interactivity and the innovativeness of the experience were also reported. None reported refining information as an advantage. Hardware performance was the primary concern (11/26, 42%), followed by user-friendliness, a lack of proactive content production, and issues related to price and health.

Lastly, regarding 3DP, the primary advantage was the possibility of customized product manufacturing (21/26, 81%). Some developers recognized high accuracy and texture fidelity, and reported increased creative freedom and fast product production. However, none mentioned new design possibilities as an advantage. The primary challenge was manufacturing costs (18/26, 69%), followed by long printing times, difficulty in creating complex models, limitations of materials, and low durability of printed objects (all 2/26, 8%).

Discussion

Overview

Our study aimed to investigate the gaps in perspectives between medical students and developers regarding satisfaction and the most anticipated future use of 3D technologies in medical education. This study offers insights into the differences in satisfaction levels between medical students and developers. This study also provides insights into how anticipations for the use of these technologies differ between medical students and developers across different situational scenarios, as well as how these technologies might be used in specific specialties or areas

of medicine. Additionally, this study sheds light on developers' viewpoints regarding the advantages and challenges associated with these technologies, with the aim of understanding their applicability and limitations in industrial settings.

Principal Findings

The results of this study provide unique evidence that medical students have a higher level of overall satisfaction than developers across VR, AR, and 3DP technologies (Figure 4), which implies that there might be a stronger alignment between the satisfaction and experiences of students with these technologies. It is also noteworthy that medical students were more satisfied than developers with esthetics and the intention to continue use among the 7 categories in VR, AR, and 3DP technologies (Figure 4). We assume that students had positive experiences with the liveliness of technology and design through this course, and based on this experience, they will have high expectations for the future in terms of the vividness and design of these technologies. We believe that students had higher satisfaction with the intention to continue use compared to developers because, as users, they perceive that these technologies yield greater learning effectiveness when used repetitively in the learning environment.

The extent of satisfaction difference between medical students and developers varied across VR, AR, and 3DP. Regarding VR, the difference in satisfaction between medical students and developers was the greatest for esthetics and conceptual understanding (desired angle). This difference could be attributed to the experience students had during the course. Students would have experienced higher satisfaction by interacting with the CHD model they created in the course, such as by rotating the CHD model they created to the desired angle in virtual space, understanding the structure, and applying color. We speculate that esthetics showed the largest extent of difference in AR because students experienced higher satisfaction than developers as the design made it easy for them to recognize and interact with the CHD models they created when presented in a real-world environment. Regarding 3DP, the difference in satisfaction was the greatest for concept understanding (desired angle) and continued use intention (repetition). The patient-customized CHD model could be rotated at any desired angle in real space, and it is assumed that continuous repetition helps students understand complex anatomy.

This study found that when comparing all categories with each technology, medical students were more satisfied than developers in reality (real world) only within VR (Figure 4). Based on the findings of the study, it can be inferred that VR technology, particularly in its current state of hardware development, offers medical students a more realistic and satisfying experience compared to developers. On the other hand, developers may be less satisfied with the current state of technology when considering both the current state of technology and the potential for future technological advances in the industry. This may be because developers who actively participate in the industry are aware of the substantial difficulty needed to increase the realism of VR. In addition, AR showed no significant difference in satisfaction between medical students

and developers in terms of understanding of the concept (desired angles) and spatial ability (Figure 4). Therefore, we conclude that VR might offer a more immersive and satisfying experience for medical students based on current hardware technologies, while AR appears to offer a more balanced perception in terms of conceptual understanding and spatial awareness.

One of the key findings of our study was that there was a gap in anticipations between medical students and developers in 6 situational scenarios regarding the anticipated future use of technology, with the exception of 1 situational scenario (Multimedia Appendix 9). Situational scenarios in which the perspectives differed included educating medical students and residents, individual and collaborative surgical planning, and performing surgery on a patient. In these scenarios, developers perceived MR as a more promising technology. In contrast, medical students perceived VR primarily for student education, 3DP for resident education and individual surgical planning, and AR for collaborative surgical planning and performing surgery on a patient. This discrepancy between the 2 groups is likely from variations in exposure and practical experience with these technologies. Although students experienced VR, AR, and 3DP in their elective course, they were not exposed to MR. Despite the limited exposure to MR among medical students, we can speculate on their perspectives regarding its future use based on their experiences. Medical students may see VR primarily for undergraduate education because of its immersive and interactive nature, allowing for realistic simulations [4]. They may see 3DP as beneficial for resident training and individual surgical planning because of its hands-on nature, allowing them to create physical models that can enhance their understanding of anatomical structures and medical conditions. This perception could be attributed to its potential for customized product manufacturing, which could potentially facilitate clearer communication of medical information to nonexperts. This result is consistent with the results of previous studies, which tended to report positive correlations between the use of 3DP and resident education and explanation to patient caregivers [28,57-59]. Regarding AR, medical students may see it as suitable for collaborative surgical planning and performing surgery on a patient because of its potential to overlay digital information onto the real surgical environment, providing surgeons with real-time guidance and information during procedures. This aligns with existing research on its benefits in specific surgical procedures, such as spine and orthopedic surgeries [60,61]. Our study implied a potential interest in exploring the application of AR in the surgical field among medical students. These findings of our study emphasize the need to align technological advancements with the expectations of both medical students and developers. By meeting the expectations of both groups, these technologies can be smoothly integrated into medical education.

This study highlights an interesting alignment in perspectives between medical students and developers, particularly in the situational scenario of explaining to a patient's caregiver. In this scenario, both groups showed potential interest in 3DP for conveying complex medical information to a patient's caregiver. Additionally, considering that students and developers in this study participated in creating patient-specific 3D-printed heart

models and that students gave group presentations with this technology, it can be inferred that personalized 3D-printed models are helpful in patients' caregiver communication. Previous studies demonstrated that the use of personalized 3DP models can further enhance patient understanding by providing tailored visual representations of individual patient anatomy and medical conditions [57,62,63].

This exploration of varying expectations will offer insights into how these technologies are anticipated to shape the future of medical training, patient care, and medical research. Several potential applications can be envisioned based on our research findings. In medical education for medical students and patients, VR, MR, and 3DP could be used for anatomy learning, medical research, simulation training, and procedural skills practice. VR can be used for virtual simulations of procedures like suturing, catheterization, and intubation, as well as clinical scenarios like patient assessments and diagnostic procedures. MR is expected to enhance anatomical learning and hands-on procedural training by combining virtual and real-world elements. It will overlay digital models onto physical specimens, which are generated from 3DP, and enable realistic simulations with them. Our speculation involves the use of AR, MR, and 3DP in surgical planning. Based on patient-specific medical imaging data, it is anticipated that surgeons will use patient-specific 3DP models to physically review and plan surgical approaches before the actual surgery. Alternatively, they may use AR and VR for surgical simulations to plan the procedure in advance. We also speculate that AR and MR will be used in specialties, such as neurosurgery, cardiovascular surgery, etc. Surgeons can use AR holograms of the heart or lungs to visualize complex cardiac anatomy during surgery and to orient and localize the target tumors or lesions. MR-guided interventions can facilitate minimally invasive procedures, such as transcatheter valve replacement, by providing real-time imaging guidance and navigation. VR and 3DP are expected to benefit patient care. We speculate that VR will help manage pain and reduce stress during treatment, while 3DP will allow for personalized models, improving the understanding of patient conditions and treatments.

While the majority of developers perceived the inherent capabilities of VR, AR, and MR technologies as strengths, an interesting aspect of our findings is that none of them mentioned providing experiences similar to real environments as a strength of VR technology or cited the refinement of information in AR technology (Multimedia Appendix 10). We infer that developers perceive providing experiences similar to real environments and refinement of information as technically challenging at present or as areas requiring further development and thus fail to recognize the benefits of each technology. In fact, modeling of environments, especially in the medical field, requires the creation of high-quality 3D objects [64]. Reaching highly realistic and natural photorealistic rendering and animations in full 3D can be exceedingly challenging and costly in terms of both time and money [65]. Therefore, we speculate that in addition to the advantages of each technology that developers currently recognize, additional improvement and development are needed for aspects of each technology that developers are not aware of at present.

This study identified a concern regarding developers' limited attention to health issues, although there is a high prevalence of computer vision syndrome as an occupational disease in the 21st century (Multimedia Appendix 10). Additionally, the focus of developers on hardware performance over health issues indicates concerning results where technical priorities overshadow user well-being. To address this, developers must adopt a more holistic approach that balances technical advancements with user safety. This includes integrating health considerations into the design and development process, implementing safety features, and conducting thorough user testing to mitigate health-related issues [66]. By prioritizing both technical excellence and user welfare, developers will enhance the overall ethical standards of these technologies and contribute to a safer and more responsible technological landscape.

Regarding 3DP, our results showed that developers perceived the practical aspect of manufacturing customized products as an advantage of 3DP over the creative aspect of new design possibilities. This finding is consistent with previous studies reporting that customization allows for printing parts with geometries tailored to each print, which can be particularly useful in patient-specific fabrications for personalized medicine, where the layout matches a specific patient's anatomy [67]. As a significant challenge, the developers in this study and several other studies recognized high manufacturing costs [68]. However, in general, 3DP has been applied in the medical field. Therefore, this study suggests the need for continued research and development efforts aimed at optimizing the cost-effectiveness of 3DP technology without compromising on its advantages.

Limitations

This study has several limitations. First, this study was conducted in a single institution with a relatively small sample size. Further studies should be conducted and compared across multiple medical schools. Second, this study was limited by the exclusive focus on first-year medical students and developers involved in the course. While this provided valuable insights into the perspectives of these specific groups, the exclusion of residents, fellows, and senior medical professionals may limit the generalizability and applicability of our findings. Participants from diverse backgrounds should be included in further studies. Third, owing to the voluntary nature of student participation in the course, participant selection was not conducted. Consequently, our study results may be influenced by the higher proportion of male individuals than female individuals in the student group, potentially resulting in a dominance of male perspectives in the outcomes. Fourth, students having difficulty distinguishing between VR, AR, and MR experiences may have influenced the accuracy of the self-reported engagement with these technologies. Future studies should consider incorporating educational interventions to enhance students' understanding of various immersive technologies before administering surveys on technology usage. Lastly, it was not possible to validate the instruments used in this study, and we used a limited number of questionnaire items to measure the levels of students' and developers' satisfaction with the elective course. Despite these limitations, this study might help to understand differences in

satisfaction levels between medical students and developers, as well as discrepancies in their perceptions of future technological advancements.

Conclusion

The roadblock for better integration of VR, AR, MR, and 3DP technologies in medical education is the gap in satisfaction levels and future anticipations between medical students and developers. Our study found that VR, AR, and 3DP technologies showed differences in satisfaction levels in the categories of esthetics and continuous use intention. In particular, in VR,

differences in satisfaction levels regarding reality (real world) emerged as a major obstacle to integration into medical education. Medical students and developers had different anticipations of the future use of technology regarding education, surgical planning, and surgery. Furthermore, insights from industry developers indicated that hardware performance poses a challenge for VR, AR, and MR, while high manufacturing cost is the primary concern for 3DP. Recognizing and understanding these discrepancies and current challenges can help developers tailor their strategies and innovations to better meet the expectations of technology users.

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Data Availability

The data used or analyzed in this study are available from the corresponding author upon reasonable request.

Authors' Contributions

YHY made substantial contributions to conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing—original draft, and writing—review and editing. DHS contributed to conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, validation, and writing—review and editing. HJC contributed to conceptualization, methodology, project administration, supervision, formal analysis, validation, and writing—review and editing. All authors approved the final version of the manuscript for submission.

Conflicts of Interest

None declared.

Multimedia Appendix 1

The process of creating a 3D reconstruction from a patient's computed tomography scan.

[[MP4 File \(MP4 Video\), 92202 KB - xr_v1i1e54230_app1.mp4](#)]

Multimedia Appendix 2

The heart of a patient with an interrupted aortic arch.

[[MP4 File \(MP4 Video\), 32727 KB - xr_v1i1e54230_app2.mp4](#)]

Multimedia Appendix 3

The heart of a patient with Ebstein anomaly.

[[MP4 File \(MP4 Video\), 33538 KB - xr_v1i1e54230_app3.mp4](#)]

Multimedia Appendix 4

The heart of a patient with transposition of the great arteries.

[[MP4 File \(MP4 Video\), 15565 KB - xr_v1i1e54230_app4.mp4](#)]

Multimedia Appendix 5

The heart of a patient with major aortopulmonary collateral arteries.

[[MP4 File \(MP4 Video\), 30007 KB - xr_v1i1e54230_app5.mp4](#)]

Multimedia Appendix 6

A survey on satisfaction with virtual reality, augmented reality, and 3D printing technologies.

[\[DOCX File , 28 KB - xr_v1i1e54230_app6.docx \]](#)

Multimedia Appendix 7

The educational background of the software and content developers in this study.

[\[DOCX File , 17 KB - xr_v1i1e54230_app7.docx \]](#)

Multimedia Appendix 8

Average satisfaction differences in virtual reality, augmented reality, and 3D printing between students and developers.

[\[DOCX File , 52 KB - xr_v1i1e54230_app8.docx \]](#)

Multimedia Appendix 9

Medical students' (n=15) and developers' (n=26) anticipation of the use of technologies in various medical contexts within 5 years. The pie charts present percentages.

[\[PNG File , 241 KB - xr_v1i1e54230_app9.png \]](#)

Multimedia Appendix 10

Developers' perceptions of the advantages and current challenges of virtual reality, augmented reality, mixed reality, and 3D printing.

[\[PNG File , 335 KB - xr_v1i1e54230_app10.png \]](#)

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Abbreviations

- 3DP:** 3D printing
- AI:** artificial intelligence
- AR:** augmented reality
- CHD:** congenital heart disease
- MR:** mixed reality
- VR:** virtual reality

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Original Paper

Brain Activation During Virtual Reality Symptom Provocation in Obsessive-Compulsive Disorder: Proof-of-Concept Study

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Abstract

Background: Obsessive-compulsive disorder (OCD) is a psychiatric disorder characterized by obsessions and compulsions. We previously showed that a virtual reality (VR) game can be used to provoke and measure anxiety and compulsions in patients with OCD. Here, we investigated whether this VR game activates brain regions associated with symptom provocation.

Objective: In this study, we aim to investigate the neural regions that are activated in patients with OCD when they are interactively confronted with a symptom-provoking event and when they are performing compulsive actions in VR.

Methods: In a proof-of-concept study, we investigated brain activation in response to the VR game in 9 patients with OCD and 9 healthy controls. Participants played the VR game while regional changes in blood oxygenation were measured using functional magnetic resonance imaging. We investigated brain activation in relation to OCD-related events and virtual compulsions in the VR game. Due to low statistical power because of the sample size, we also reported results at trend significance level with a threshold of $P < .10$. Additionally, we investigated correlations between OCD severity and brain activation.

Results: We observed a trend for increased activation in the left amygdala ($P = .07$) upon confrontation with OCD-related events and for increased activation in the bilateral amygdala ($P = .06$ and $P = .09$) and right insula ($P = .09$) when performing virtual compulsive actions in patients with OCD compared to healthy controls, but this did not attain statistical significance. The amygdala and insula activation did not correlate with OCD severity.

Conclusions: The findings of this proof-of-concept study indicate that VR elicits brain activation in line with previous provocation studies. Our findings need to be replicated in a study with a larger sample size. VR may be used as an innovative and unique method of interactive symptom provocation in future neuroimaging studies.

Trial Registration: Netherlands Trial Register NTR6420; <https://onderzoekmetmensen.nl/nl/trial/25755>

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KEYWORDS

virtual reality; obsessive-compulsive disorder; VR; symptom provocation; MRI; neuroimaging; OCD

Introduction

Obsessive-compulsive disorder (OCD) is a chronic, debilitating disorder characterized by obsessions, recurring involuntary thoughts that are frequently linked to compulsions—mental or physical acts to control provoked emotions of fear or restlessness. The obsessions and compulsions are often

accompanied by feelings of anxiety and uncertainty and cause a high level of suffering [1]. OCD has a 2%-3% lifetime prevalence and is associated with significant impairment in social and occupational functioning [2].

An OCD diagnosis is usually based on an interpretation of clinical signs and symptoms as retrospectively expressed by the patient. Assessment by a clinician while patients are actually

experiencing symptoms in the consulting room may provide a more realistic image of the symptoms and improve the diagnostic process. This can be achieved by symptom provocation [3].

Virtual reality (VR) is one way of achieving symptom provocation in patients with OCD. There are numerous examples of studies that have investigated the use of VR to provoke OCD symptoms in order to improve an OCD diagnosis or provide targeted treatment. For example, Laforest et al [4] showed that exposure to a virtual contaminated toilet in a VR immersion chamber led to an increase in anxiety and heart rate in patients with OCD with contamination fear compared to that in healthy controls.

Furthermore, in a systematic review and meta-analysis by Dehghan et al [5], it was found that VR environments were capable of significantly increasing anxiety, disgust, uncertainty, washing urges, time spent on checking, and the number of checks in patients with OCD compared to healthy controls.

In 2 former studies, we investigated an interactive VR game designed to provoke and assess OCD symptoms in a controlled and standardized way [6,7]. Figures 1 and 2 show a schematic outline and screenshots from the VR game. The VR game is designed to actively confront patients with OCD-related events

in a standard household environment. It is a first-person-perspective game composed of video images of an actual house. Patients are asked to carefully check the house, which is left behind in a hurry by a friend. They walk through the house in a preset order and are confronted with 15 OCD-related events (eg, turning off the gas stove). Patients are asked to solve these events and subsequently check or repeat the events as often as desired (for full details, see van Bennekom et al [7]). We showed that this VR game, when played on a laptop screen, was able to provoke higher levels of anxiety and virtual compulsions in patients with OCD than in healthy controls [6,7].

In this study, we modified the VR game to enable performance inside a functional magnetic resonance imaging (fMRI) scanner. In contrast to traditional “passive” fMRI symptom provocation tasks mostly using images, written verbal stimuli, emotional faces, or neurocognitive tasks with emotional interference [8,9], this VR game is interactive and realistic and therefore actively immerses patients whilst inside the scanner. This allows us to gain insight in to blood oxygenation level-dependent (BOLD) derived brain activation while patients are confronted with OCD-related events and while they perform virtual compulsive actions. To our knowledge, this is the first study using a VR game with fMRI for symptom provocation in OCD.

Figure 1. A 3D map of the house indicating obsessive-compulsive disorder-related items. 1: locking the gate (start); 2: locking the front door (start); 3: switching off the television; 4: extinguishing the candle; 5: organizing pencils; 6: closing the window; 7: cleaning the breakfast table; 8: turning off the gas stove; 9: organizing the cans; 10: cleaning the sink; 11: hand-washing after using the toilet; 12: switching off the flat iron; 13: organizing hazardous substances; 14: locking the front door (end); and 15: locking the gate (end).



Figure 2. Screenshots from the virtual reality game.

Recent meta-analyses of fMRI, positron emission tomography, and single-photon emission computed tomography studies underline several brain regions involved in the pathophysiology of OCD. Abnormalities in cortico-striato-thalamo-cortical pathways—circuits connecting the cortex, striatum, basal ganglia, and thalamus—are involved in the pathophysiological substrate [10]. In a recent meta-analysis of fMRI, positron emission tomography, and single-photon emission computed tomography studies conducted by Thorsen et al [9], brain activation during symptom provocation was compared between patients with OCD and healthy controls. They found higher levels of activation in the bilateral amygdala, right putamen, orbitofrontal cortex (OFC) extending into the anterior cingulate cortex (ACC) and ventromedial prefrontal cortex, and middle temporal and left inferior occipital cortices during emotional processing in patients than in healthy controls. In patients with OCD with a higher rate of comorbidity with anxiety or mood disorders, they found more pronounced activation in the right putamen, amygdala, and insula. Another preceding smaller meta-analysis of neuroimaging symptom provocation studies in OCD, conducted by Rotge et al [11], also found an increased likelihood of activation in 19 clusters in patients with OCD compared to healthy controls. These included the OFC, ACC, precuneus, and thalamus. Although paradigms have been developed to induce the urge to check in patients with OCD [12], to our knowledge, no provocation procedures to induce actual checking behavior have been applied in fMRI studies before.

Because our VR game represents a new and innovative technique for fMRI symptom provocation, we decided to perform a proof-of-concept study with a limited sample size. In this study, we aim to investigate the neural regions that are activated in patients with OCD when they are interactively confronted with a symptom-provoking event and when they are

performing compulsive actions in VR. Moreover, we aim to investigate whether activation in these regions is related to OCD symptom severity. We hypothesized that (1) playing the VR game inside a fMRI scanner would lead to increased brain activity within the OFC, ACC, amygdala, right putamen, and right insula in patients with OCD compared to that in healthy controls, and (2) a positive correlation exists between the degree of brain activation and the severity of OCD in patients.

Methods

Participants

We recruited 9 patients with OCD from December 2017 to March 2020 at the Psychiatric Outpatient Department of Amsterdam University Medical Center by means of information letters provided by their treating clinicians. Patients were also recruited through the Dutch OCD website Dwang.eu [13]. This sample size is in line with recommendations for proof-of-concept fMRI studies [14]. All included patients had a primary diagnosis of OCD, as determined by a psychiatrist and confirmed by the Mini-International Neuropsychiatric Interview in accordance with the DSM-IV (Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition) criteria [15]. We aimed to assess a clinically relevant group of patients with OCD including those with (mild to moderate) comorbid psychiatric disorders, under the condition that OCD was the primary diagnosis. We recruited 9 age- and gender-matched healthy controls through advertisements at the Amsterdam University Medical Center and by emailing individuals who formerly participated in research projects at our department. The healthy controls were free of any current mental disorders, as validated with the Mini-International Neuropsychiatric Interview. We excluded subjects with a history of severe neurological or cardiovascular disorders, psychotic disorder,

bipolar disorder, intellectual disability, and alcohol or substance abuse during the last 6 months. Furthermore, the use of medication potentially influencing cerebral blood flow, uncorrected hearing or vision problems, and irregular sleep/wake rhythm were exclusion criteria, as well as other contraindications for scanning with a magnetic resonance imaging (MRI) scanner.

Ethical Considerations

The study was approved by the Medical Ethics Committee of the Academic Medical Center of the University of Amsterdam (case number NL59652.018.16). All participants provided written informed consent before enrollment.

Procedure

The procedure of fMRI scanning was carried out at the Spinoza Centre for Neuroimaging, Amsterdam, the Netherlands. On the test day, trained clinical researchers obtained clinical and demographic data using questionnaires. After that, participants practiced controlling the VR game through manual button boxes in a mock scanner. For baseline measurements, they first watched a calming movie with nature scenes inside the scanner. Finally, they played the VR game during an fMRI scanning session. Trained technicians at the Spinoza Centre for Neuroimaging performed the scanning procedure in the presence of a trained researcher.

Patient and Public Involvement

Patients or the public were not involved in the design, conduct, reporting, or dissemination plans of our research.

Assessments

Clinical Data

Trained clinical researchers assessed OCD severity using the Yale-Brown Obsessive Compulsive Scale (Y-BOCS) and OCD subtype using the related Y-BOCS Symptom Checklist (Y-BOCS-SC) [16], in combination with an expert's opinion. They measured anxiety and depression symptoms with the Hamilton Rating Scales for anxiety [17] and depression [18]. Finally, the sense of presence was measured with the Igroup presence questionnaire [19].

VR Game

The setup of the VR game is described and illustrated in detail in our pilot study [7]. In short, it concerned a first-person-perspective video game based in a house with 15 OCD-related events. Participants walked a set route through the house and were confronted with all these events in a preset order. At every event, after confrontation, participants were asked if they wanted to correct and then check an event, or if they wanted to proceed to the next event without intervening. Checks could be repeated as often as desired. At each event, participants rated their emotional responses including anxiety, tension, uncertainty, and urge to control on a digital 0-10 visual analog scale (VAS) after confrontation, correction, and checking. The VR game's output scores included the VAS scores and the number of virtual compulsive actions performed.

For this study, we edited the output data of the VR game to allow communication with the fMRI scanner. After 35 minutes, both the game and scanning process were automatically stopped.

Participants could see the white projection screen behind the head through a mirror fixed at a 45° angle to the head coil (standard MRI equipment). The VR game provides an immersive virtual reality "feel" because it has a first-person perspective and is projected close to the eyes in the scanner. The participant operated the VR game by means of 2 manual button boxes.

Acquisition of Images and Preprocessing

MRI scanning was performed using a 3.0T MRI scanner (Philips) using a 32-channel SENSE head coil. Scanning included a high-resolution T₁-weighted structural scan for anatomical reference (repetition time=6.9 milliseconds, echo time=3.1 milliseconds, voxel size=1.20 mm isotropic, flip angle=8°, and 150 transverse slices). Additionally, at least 496 (range 496-883) BOLD scans were acquired using a T₂*-weighted gradient multiecho echoplanar imaging sequence [20], with the following parameters: repetition time=2375 milliseconds, echo time=9/26.4/43.8 milliseconds, flip angle=76.1°, field of view=224 × 224 × 122 mm³, voxel size=2.8 × 2.8 × 3.0 mm³, matrix size=76 × 73, slice thickness=3 mm, slice gap=0.3 mm, number of slices=37, acquired in foot-head order. There was a maximum time frame of 35 minutes for playing the VR game inside the scanner.

We performed imaging analysis using Statistical Parametric Mapping (version 12; Wellcome Trust Centre for Neuroimaging). Data preprocessing consisted of realignment of images with respect to the middle volume, slice timing correction, coregistration of echoplanar imaging data to structural T₁ data, normalization to Montreal Neurological Institute space (3 mm isotropic), and spatial smoothing using an 6-mm full width at half maximum Gaussian kernel. We checked for motion artifacts; for a patient with OCD, we had to omit the final 25% of the VR game scans, due to excessive motion artifacts (ie, >5-mm framewise displacement).

Data Processing and Statistical Analysis

Clinical and VR Game Data

Demographic, clinical, and VR game data were analyzed using SPSS (version 26; IBM Corp). The VAS score of each emotional response upon confrontation with an OCD-related item was averaged for the 15 items. We performed Bonferroni correction to correct for testing of multiple emotional responses. Because of the small sample size, nonparametric tests were used to compare patients with healthy controls. We used the Mann-Whitney *U* test to compare continuous data (age and emotional responses) and Fisher exact tests for comparing categorical data (sex, nationality, schooling, and number of compulsions), including categorized questionnaire scores, because original scores did not qualify as continuous due to their limited distribution. Furthermore, in the group of patients with OCD, we calculated the reduction in emotional responses by subtracting the VAS score after the last compulsive action from the VAS score at confrontation. We used a 1-sample Wilcoxon signed rank test to assess the reduction in emotional responses after performing compulsive actions. The α value was set at .05 for significance.

Neuroimaging Data

Functional MRI data were analyzed using Statistical Parametric Mapping software (version 12) [21]. We performed individual subject analyses within the context of the general linear model, using delta functions convolved with a canonical hemodynamic response function to model events of interest. To enable this first-level analysis, we subdivided the events in the game in confrontation, correction, checking and, VAS rating events (Figure 3), which were contrasted with short time frames in the game during which no specific events took place. This resulted in a total of 10 regressors.

On the second-level between-group comparison, we conducted an independent samples *t* test to determine whether the OCD-related events in the VR game influenced brain activation differently between patients with OCD and healthy controls.

Figure 3. Events in the virtual reality game. VAS: visual analog scale.



Results

Demographic and Clinical Data

Demographic and clinical data of the study participants are shown in Table 1. Patients showed significantly more obsessive-compulsive and depressive symptoms; however, anxiety symptoms (assessed using the Hamilton Rating Scale for Anxiety) and mean scores of the Igroup Presence Questionnaire did not categorically differ significantly between patients and healthy controls ($P=.21$ and $P=.17$, respectively).

We investigated group interactions using a priori regions of interest (ROIs). We defined the bilateral amygdala, OFC, ACC, right putamen, and right insula as a priori ROIs. We used a threshold of 0.01 (0.05 divided by 5; corrected for multiple ROIs) for significance. To accommodate the low statistical power due to the small sample size, we also reported results at a trend significance level with a threshold of $P<.10$. We corrected for multiple comparisons at the voxel level (family-wise error) using a small-volume correction for ROIs, which were based on the automatic anatomical labeling atlas [22], using the WFU Pickatlas tool [23]. To determine correlations of Y-BOCS scores with fMRI data in SPSS, we used Marsbar [24] to extract parameter estimates from the bilateral amygdala and right insula in patients with OCD. To determine correlations of the fMRI data with the Y-BOCS scores, the Spearman correlation coefficient was used.

Patients with OCD had a mean Y-BOCS score of 23, which indicates moderate symptom severity. All patients had symptoms from multiple OCD dimensions. The most common dominant dimensions included perfectionism or symmetry for 44.4% ($n=4$) and taboo thoughts (aggressive or sexual intrusions) for 33.3% ($n=3$) of patients with OCD. Five patients with OCD were treated with a selective serotonin reuptake inhibitor (SSRI) or serotonin and norepinephrine reuptake inhibitor (SNRI), and 4 patients were unmedicated. Four patients experienced comorbid disorders including generalized anxiety disorder, depression, and social anxiety.

Table 1. Demographic and clinical data of patients with obsessive-compulsive disorder and healthy controls.

| Characteristics | Patients (n=9) | Controls (n=9) | <i>P</i> value |
|--------------------------------------|----------------|----------------|----------------|
| Age (years), mean (SD) | 29 (8.0) | 29 (8.5) | .97 |
| Male sex, n (%) | 4 (44) | 4 (44) | >.99 |
| Dutch nationality, n (%) | 8 (89) | 9 (100) | >.99 |
| Tertiary education, n (%) | 3 (33) | 5 (56) | .64 |
| HAM-A ^a score, mean (SD) | 12 (7.5) | 1 (2.0) | .21 |
| HAM-D ^b , mean (SD) | 11 (4.5) | 1 (2.1) | .002 |
| Y-BOCS ^c score, mean (SD) | 23 (2.8) | 0 (0) | <.001 |
| IPQ ^d score, mean (SD) | 1.97 (0.96) | 1.53 (0.75) | .17 |

^aHAM-A: Hamilton Rating Scale for Anxiety.

^bHAM-D: Hamilton Rating Scale for Depression.

^cY-BOCS: Yale-Brown Obsessive Compulsive Scale.

^dIPQ: Igroup Presence Questionnaire.

VR Game Data

The provoked emotional responses when playing the VR game are shown in Table 2. These represent the difference in mean VAS scores at confrontation over all 15 items and VAS scores

at the baseline measurement. Playing the VR game provoked significantly more anxiety, but not tension, uncertainty, and an urge to control in patients with OCD compared to healthy controls. Furthermore, patients with OCD showed significantly more compulsive behavior in the VR game than healthy controls;

patients performed a mean of 0.46 (SE 0.14) compulsions per event, healthy controls performed a mean of 0.07 (SE 0.02) compulsions per event ($P=.03$). Finally, in patients with OCD, we found a significant reduction in anxiety (mean 1.54, SE 0.60; $P=.001$), unrest (mean 3.09, SE 0.77; $P=.008$), and uncertainty (mean 1.72, SE 0.61; $P=.01$) but not in the urge to control (mean 2.16, SE 0.86; $P=.02$) after performing virtual compulsive actions.

Table 2. Provoked emotional responses during the virtual reality game measured using the visual analog scale (VAS).

| | VAS scores of patients with obsessive-compulsive disorder (n=9), mean (SE) | VAS scores of controls (n=9), mean (SE) | U value | P value |
|--------------------------------|--|---|---------|---------|
| Change ^a in anxiety | 1.01 (0.38) | 0.13 (0.30) | 12.0 | .01 |
| Change in tension | 0.78 (0.72) | 0.21 (0.35) | 36.0 | .73 |
| Change in uncertainty | 1.47 (0.57) | -0.03 (0.19) | 19.0 | .06 |
| Change in the urge to control | 1.58 (0.63) | 1.31 (0.37) | 38.0 | .86 |

^aDifference between scores at baseline and at confrontation.

Neuroimaging Data

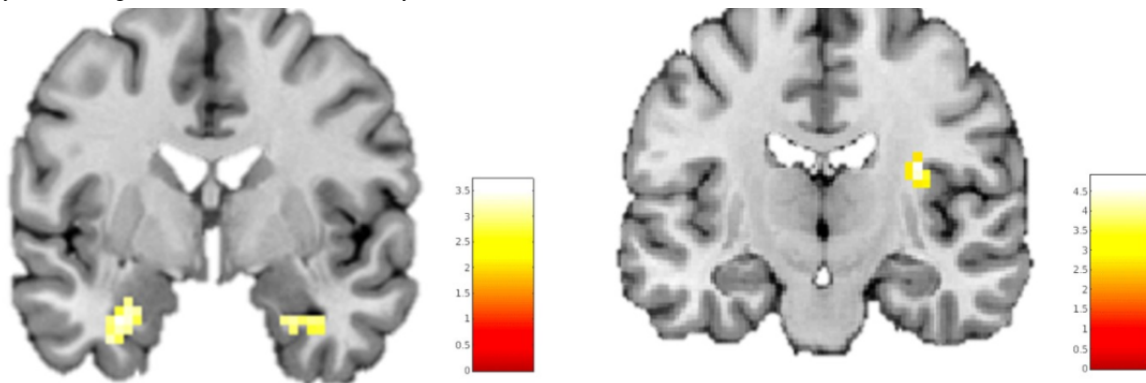
Since 4 patients were unable to finish the VR game within 35 minutes, patients with OCD were exposed to a mean total number of 13.89 (SD 1.27) events during the VR game scan, whereas all healthy controls were exposed to all 15 (SD 0) events. After correction for multiple comparisons, there were no significant differences in brain activation between patients with OCD and healthy controls when playing the VR game. However, during confrontation with the OCD-related events in the game, a larger increase in left amygdala activity was observed in patients with OCD than in healthy controls at the trend level (Figure 4; peak voxels: x, y, and z=-27, -4, and -25;

$T=3.24$; $P_{fwe,svc}=.07$). When performing the virtual compulsive actions, a larger increase in left amygdala (Figure 5A; peak voxels: x, y, and z=-27, -4, and -22; $T=3.61$; $P_{fwe,scv}=.06$), right amygdala (Figure 5A; peak voxels: x, y, and z=30, -4, and -28; $T=3.27$; $P_{fwe,svc}=.09$), and right insula (Figure 5B; peak voxels: x, y, and z=33, -19, and 20; $T=4.61$; $P_{fwe,svc}=.09$) activity was observed in patients with OCD than in healthy controls at trend level. Task-related activity in the ROIs OFC, ACC, and right putamen was not significantly increased in patients with OCD compared to that in healthy controls. Finally, healthy controls showed no areas of increased BOLD response upon confrontation with OCD-related events or when performing virtual compulsive actions compared to patients with OCD.

Figure 4. Results of analysis of regions of interest. Trend significant cluster of hyperactivation in the left amygdala in patients with obsessive-compulsive disorder (OCD) compared with healthy controls during confrontation with OCD-related events. Montreal Neurological Institute coordinate: y=-4.



Figure 5. Results of analysis of regions of interest. Trend significant clusters of hyperactivation in patients with obsessive-compulsive disorder compared with healthy controls during performance of virtual compulsive actions, in the left and right amygdala (A; Montreal Neurological Institute [MNI] coordinate: $y=-4$) and right insula (B; MNI coordinate: $y=-19$).



Correlation Between Y-BOCS Scores and Brain Activation

Based on the aforementioned results, we focused on the correlation between amygdala and insula activation and Y-BOCS scores in patients with OCD. Upon confrontation with OCD-related items, there was no significant correlation between left amygdala activation and the Y-BOCS score ($r_s=-0.542$, $P=.13$). When performing virtual compulsive actions, there were no significant correlations between left amygdala ($r_s=-0.192$, $P=.65$) or right amygdala ($r_s=-0.419$, $P=.30$) and right insula ($r_s=-0.467$, $P=.24$) activation and Y-BOCS scores.

Discussion

Principal Findings

In this study, we performed an fMRI scanning session during a VR game for OCD, allowing us to examine brain regions upon confrontation with virtual symptom-provoking events and compulsions. We replicated findings from our previous study, showing that this VR game provoked more anxiety and virtual compulsive actions in patients with OCD than in healthy controls [6]. In the patient group, we also found a decrease in negative emotions following compulsive actions. Our results confirm that the VR game can provoke anxiety and virtual compulsions, which modulate negative emotions. We found no significant differences in brain activation between patients with OCD and healthy controls. The results show increased activity in the bilateral amygdala and the right insula at the trend level. We found an increase in left amygdala activity upon confrontation and an increase in bilateral amygdala and right insula activity with compulsive actions in patients with OCD. Contrary to our hypothesis, we did not find differences in brain activity in the OFC, ACC, and right putamen.

Comparison to Prior Work

The increase in left amygdala activity in response to confrontation is in line with previous symptom provocation studies [9]. The amygdala is involved in the detection of salient events and the mediation of negative emotions such as fear and anxiety [25,26]. The activity is associated with increased attention toward events and provoked feelings of anxiety. The laterality of the amygdala's response may be explained by fear

modulation of the left amygdala in response to learned, subject-dependent, aversive stimuli, in contrast to fear modulation by the right amygdala in generally aversive stimuli [27]. Increased bilateral amygdala and right insula activity during virtual compulsive actions is in line with previous provocation studies [9]. In our study, we observed brain activity while participants actually performed virtual compulsions. This is unique, since other studies use pictures, emotional faces, or written words to provoke symptoms. Our approach is a good example of an ecologically valid experiment that shows engagement of the amygdala and insula.

Thorsen et al [9] found pronounced right insula activation in studies with comorbid anxiety or mood disorders. In another study, the right insula was activated in response to disgust-inducing pictures in patients with contamination fear [28]. Indeed, the insula is suggested to play a role in processing disgust, and, in particular, the contamination/washing dimension of OCD is associated with higher disgust sensitivity [29]. Furthermore, Luigjes et al [30] found increased insula activation during risk processing in risk-averse patients with OCD, mainly in those with the doubt/checking dimension of OCD. The disgust and high risk-related virtual compulsions in our VR game (eg, washing hands after touching a dirty toilet or turning off a running flat iron) could have contributed to right insula activation.

In contrast to former studies, we did not find a difference in activity in the OFC or ACC. Most neuroimaging symptom provocation studies found increased activity in the OFC and ACC [9,11]. In one study, hypoactivation of the left ACC was observed in response to a handshake from a dirty virtual avatar in patients with OCD [31]. Furthermore, we did not find a correlation between the degree of brain activation and severity of symptoms. These results are nevertheless consistent with those of the meta-analysis of Thorsen et al [9]; the latter did not find a correlation between amygdala or insula activity and symptom severity.

Limitations

Our study has a few limitations. First, since this is a proof-of-concept study, we decided to recruit a small sample of 9 patients with OCD and 9 healthy controls, leading to limited statistical power. This impedes drawing definite conclusions regarding the ability of the VR game to activate the OCD-related

neural regions in patients compared to healthy controls. This could also explain why only trend-level activation patterns were observed in the amygdala and insula.

Second, in our group of patients with OCD, 5 patients used a SSRI or SNRI and 4 experienced a comorbid anxiety or mood disorder. Thorsen et al [9] found a negative correlation between SSRI use and right amygdala activation, and more pronounced right amygdala and less pronounced left amygdala activation in studies with more comorbid anxiety and mood disorders. Hence, in our results, both medication use and comorbid disorders could have affected left and right amygdala activation. Third, we used the “neutral” scenes (eg, the camera turning toward a wall) as contrast in the analyses during the game, and we cannot exclude the premise that participants already anticipated new events during the neutral scenes. If anything, this would have led to less pronounced activation patterns in the OCD-related brain regions in response to OCD-related events than to neutral events. Finally, 4 out of 9 patients with OCD indicated that their specific obsessions and compulsions were not triggered by the VR game. This indicates that the VR game, despite its comprehensive design, is not able to trigger OCD in all patients, possibly because the VR game did not represent all OCD dimensions. Indeed, studies have found distinct patterns of brain activation with OCD dimension-specific picture sets [32] or fully individualized picture sets [8].

Conclusions

In this proof-of-concept study, the VR game activated the bilateral amygdala and right insula at the trend level in patients with OCD, especially when performing virtual compulsions. Since this was a proof-of-principle study with 9 patients, it is

important to replicate these results in studies with a larger sample size. Our results suggest that immersive symptom provocation, with the possibility to conduct virtual compulsive actions, may allow us to study brain regions in patients with OCD in a more ecologically valid context, and, as such, can be seen as a stepping stone toward more research in this area. In particular, the possibility to observe brain activation when performing virtual compulsive actions might teach us more about the involved brain regions in this complex process that has proved difficult to study in an MRI scanner. So far, the VR game was not able to activate the whole OCD circuit including the OFC and ACC, possibly due to limited power because of the small sample size.

To our knowledge, this is the first study among patients with OCD using an innovative and interactive VR game entailing multiple OCD dimensions for symptom provocation inside a MRI scanner. New possibilities arise, for example, with the development of MRI-suitable head-mounted displays, to gain even higher levels of presence and immersion inside the MRI scanner. Furthermore, new VR technology allows for personalization of the virtual environment to the OCD dimension, which may improve power to detect brain regions [8]. Further research with larger sample sizes is needed to determine whether using a virtual environment on a head-mounted display that can be adjusted to OCD subtypes will lead to increased activation of neural regions related to OCD. If activation of OCD-related neural regions can be achieved during confrontations with events and while performing compulsive actions in a VR environment, this suggests the feasibility of exploring the neural basis of near-real-life OCD symptoms. This approach could yield deeper insights into the complex pathological foundations of OCD.

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Data Availability

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

Authors' Contributions

MJvB drafted the manuscript, led the investigation and formal analysis, and supported the conceptualization of the study. GvW and WBB supported the formal analysis and reviewed and edited the manuscript. JL led the development of the study methodology, supervised the study, and reviewed and edited the manuscript. DD conceptualized and supervised the study, and reviewed and edited the manuscript.

Conflicts of Interest

GvW received research funding from Biogen, Bitbrain, and Philips for unrelated work. The other authors declare they have no conflicts of interest.

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Abbreviations

ACC: anterior cingulate cortex

BOLD: blood oxygenation level-dependent

DSM-IV: Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition

fMRI: functional magnetic resonance imaging

MRI: magnetic resonance imaging

OCD: obsessive-compulsive disorder

OFC: orbitofrontal cortex

ROI: region of interest

SNRI: serotonin and norepinephrine reuptake inhibitor

SSRI: selective serotonin reuptake inhibitor

VAS: visual analog scale

VR: virtual reality

Y-BOCS: Yale-Brown Obsessive Compulsive Scale

Y-BOCS-SC: Yale-Brown Obsessive Compulsive Scale Symptom Checklist

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Virtual Reality in Clinical Teaching and Diagnostics for Liver Surgery: Prospective Cohort Study

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Abstract

Background: Learning and applying anatomy are essential but are studied and done through 2D tools and imaging techniques. This study aims to verify the usefulness of an additional 3D technique and ensure an improvement in the visualization of anatomical structures and pathological findings.

Objective: The study aims to examine the usefulness of virtual reality (VR) technology as an additional tool in medical diagnostics. Groups of students, residents, and specialists in surgery, radiology, and internal medicine evaluated magnetic resonance imaging (MRI) by answering a multiple-choice questionnaire. Subsequently, a virtual 3D display was used for processing. The questionnaire focused on topographical conditions and the transfer of academic knowledge into clinical application. The main objective was to determine anatomical understanding in a comparison between sectional image (2D) presentation and additional VR (3D) presentation, measured through correctly answered questions and processing time. The system usability scale (SUS) was integrated as another criterion for VR usability.

Methods: The cross-over study assessed 63 participants regarding their knowledge of liver anatomy and pathologies based on an interindividual comparison. Group formation according to the respective level of medical training was as follows: students (n=35), residents (n=15), and specialists (n=13). Participants answered 25 multiple-choice questions first using sectional imaging (MRI) in a 2D environment (computer screen) and afterward with the respective segmented 3D model visualized in a VR simulation. The main criteria for the analyses were the number of correctly answered questions and processing time. A customized SUS was used to analyze VR usability. Missing data analysis showed that there were no accounted missing data.

Results: The rate of correct answers improved significantly with the additional use of VR ($F_{1,59}=314.376$; $P<.001$). Using MRI, a significant difference was observed between students and residents ($P=.04$) and between students and specialists ($P<.001$). In the VR condition, no significant differences between groups were found. In the MRI condition, significant differences in processing time were observed between students and specialists ($P=.02$) and between residents and specialists ($P=.04$). No differences existed between students and residents. With VR, processing time decreased significantly in all groups ($F_{1,59}=280.700$; $P<.001$). Significant differences between students and specialists ($P=.02$) and between students and residents ($P=.004$) remained. No notable differences between residents and specialists ($P=.72$) were found. The SUS showed a subjectively simplified answerability of the questions with additional use of VR. The usefulness and benefits for an additional use of VR were stated.

Conclusions: The additional use of VR suggests statistically significant improvements across all groups. VR seems to enable students and residents to participate in diagnostics and create treatment plans at an early stage. Transferred to clinical practice, this may lead to improvement in diagnostics and interventions. The lack of randomization and a potential learning effect are the main limitations to be addressed in future studies.

Trial Registration: German Register of Clinical Studies DRKS00030024; <https://drks.de/search/de/trial/DRKS00030024>

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KEYWORDS

VR; virtual reality; multiple-choice test; anatomy; patient-specific 3D visualization; MRI-based segmentation; liver; cohort study; visualization; tool; medical diagnostic; questionnaire; usability; diagnostics; surgery; 3D; MRI; magnetic resonance imaging

Introduction

Background

Medical students invest significant time and effort in learning theoretical human anatomy. Usually, students have the classical 2D-anatomy atlases as well as lectures at the university as their primary learning method. An additional concept at medical schools is learning anatomy and especially topographical understanding through dissection courses or by working with preprepared cadaver parts as learning material. The transfer of theoretical knowledge to an activity, in this case, dissection, supports the learning process in the context of “learning by doing” [1]. Following the university education, a further learning process takes place within the framework of specialized further education. Especially in areas of surgery and radiology, but also for any medical specialty, an extraordinary level of knowledge of human anatomy, as well as the transfer of what has been learned to the respective patient, is indispensable for the success of diagnostics and therapy [2-4]. Sectional imaging techniques such as computed tomography (CT)/magnetic resonance imaging (MRI) used in a 2D environment (computer screen) are emerging in clinical practice as a basic tool for preparing and planning surgery and interventions. Here, among other things, guidelines prescribe the use of this conservative imaging for the evaluation of disease stages and indication for further therapies (staging) [5]. However, students and residents often find this challenging. Working with conservative imaging modalities for diagnostic purposes, such as MRI, requires good anatomical knowledge and a strong ability to transfer what is learned to a sectional view. Furthermore, the mental transition to a 3D picture is essential for the correct interpretation of the sectional image and further for the application of the gained information for practical interventions. In these different stages of applying what has been learned, the necessary change of dimensions can lead to significant problems [6,7]. In the theoretical framework of the cognitive load theory, a limit of working memory is stated, which affects learning and skill acquisition in correlation with the complexity of what is being learned. The difficulty of transferring what has been learned into a clinical setting can be cognitively overwhelming [8-10]. Considering the increasing technologization, gamification of learning tools is being worked on worldwide. The first studies regarding improved learning success with the help of computer games were already conducted in the 1980s [11]. 3D computer games motivate, are enticing, and convey 3D aspects well [6,8]. In the medical field, the use of a virtual 3D atlas (virtual reality [VR] atlas) for learning human anatomy is particularly interesting. Worthy of mention is the work of Höhne et al [12-14], who created 3D models for educational reasons from CT scans. Studies have shown that

students who used a 3D atlas had better 3D visualization and anatomical-functional understanding [6,15,16]. In addition, learning with VR atlases increases learning satisfaction as well as efficiency and effectiveness, and VR-assisted learning is considered a useful adjunct to conventional anatomy instruction in dissection courses [17-19] and can reduce the cognitive load and improve learning success [8,20,21]. Taking this further, patient-specific datasets, for example, from conservative MRI can be segmented and transformed into 3D form, which can be examined in VR [22].

Objectives

The objective of this paper is to examine the usefulness of VR technology as an additional tool in medical diagnostics. In this study, students, residents, and specialists in general and visceral surgery, radiology, and internal medicine evaluated magnetic resonance images by answering a multiple-choice (MC)-based questionnaire. Subsequently, a virtual 3D display was used for processing. The questionnaire was evaluated in terms of topographical understanding and the transfer of knowledge from university or the advanced training to clinical aspects. As analysis criteria, we used the number of correctly answered questions and the processing time. We included the system usability scale (SUS) as another criterion for the usability of VR [23,24]. The main objective was to check the anatomical understanding in a comparison between a 2D presentation and an additional VR (3D) presentation, measured by the number of correctly answered questions and response time based on the MC questions.

Methods

Study Design and Procedure

Study Design

The study design was based on an interindividual comparison in the form of a cross-over design. The experiment was conducted in 2 parts, which were performed after each other, within a time frame of approximately 1 hour. In both parts of the experimental design, a total of 25 MC questions were answered.

In the first part, the participants were provided with the sectional imaging of an MRI presented on a 2D computer screen to answer the mentioned 25 MC questions. In the second part, we presented the respective segmented 3D model of the liver converted from MRI data and visualized in a VR simulation with VR goggles (HTC Vive Pro). In our experimental setup, participants found themselves in a simulated operating room with a virtual representation of a body on the operating table (Figure 1).

Figure 1. Exterior view from the study director on a person in the virtual reality environment; virtual representation of the operating room, participant and sequenced liver, digital menu for case selection, and questions projected on the wall.



Controllers, which were held in both hands, allowed objects to be lifted and moved. During the inspection of the described liver anatomy, the virtual image of the liver appeared, floating in the operating room. A menu in the VR itself could be used to switch between the individual case data. Questions to be answered appeared on the wall of the operating room and were controlled externally to the VR scene by the study director. Questions were answered verbally and were noted on paper by the study director. Regarding time manageability, a maximum time of 3.5 minutes was provided per patient case, including 5 questions in each setting. We adhered to the general rules of the Institute for Medical and Pharmaceutical Examination Questions in developing the answer modalities, ensuring that, per question, only 1 answer option was classified as correct. Double negations were not used. Other types of questions were not used in the questionnaire. Questions that remained unanswered due to the time limit were marked as “wrong.” There was also the option to rate individual questions as “unanswerable,” this answer was also rated as “wrong” in the analysis.

Eventually, an adapted version of the SUS with 6 questions answerable on a 7-point Likert scale was answered by the participants, as well as 6 questions regarding the general benefits of the VR and MRI conditions [23,24].

VR Environment

The development and the design of the atlas itself were already described by Gloy et al [16]. This version of the anatomy atlas encompassed various features for the interaction with the anatomical dummy (see the walk-through video in [Multimedia Appendix 1](#)). Since then, the application has been further developed and expanded to include patient-specific 3D liver models that follow the mentioned interaction rules and the quiz described earlier.

The internal anatomy (tumors, blood vessels, and parts of the biliary tract system) of the patient-specific liver models was visualized with realistic lighting and unique opaque solid colors. On the other hand, the liver surface was visualized with back-to-front transparency, with a low opacity of 20%, where the light shade was also determined by the same realistic lighting model. In the case of the segmented view, the system rendered

the liver surface with unique solid colors that corresponded to the segment, with the same opacity level as mentioned earlier. We iteratively tuned the rendering parameters to find the best compromise between making the liver contour, individual segments, and internal anatomy clearly visible.

The time required to create each model was approximately 1 day per model. A semiautomated process was used, where an algorithm recognized the structures of the reference MRI and converted them into a 3D model. The accuracy of the recognized structures was ensured by a radiological technical assistant. Thanks to the use of advanced software, it is now possible to segment a model in just 15 minutes.

VR was chosen in this study due to a high grade of immersiveness and interactivity as well as immersion. This provides an extraordinary perception of depth, which is lost by simply showing a 2D image or a 3D image viewed on a simple computer screen. Due to the external development of the VR software, there will be no distribution of the VR atlas.

Selection of Participants

When planning the number of participants, we decided on 40 students for pragmatic reasons. Further, a possible recruitment of 20 physicians was assumed. On the one hand, the planned number aligns with the usual cohort size for such user-centered studies. On the other hand, the recruitment of 60 study participants is considered realistic. Furthermore, there are few reliable data on the use of VR in anatomy teaching as well as in clinical applications, so reliable case number planning was not possible. During the study, preliminary analyses already showed clear results among the students, making further recruitment unnecessary.

Participants were all located within the health care system of Germany. As an overview of medical training in Germany, it should be mentioned that the degree program lasts 6 years of university studies, with students gaining their first clinical experience from the third year onward. Specialist training programs vary in length, typically lasting between 5 and 6 years. The study participants were selected so that each group was represented. The first group consisted of medical students in their fourth to sixth year. Residents from the departments of general and visceral surgery, internal medicine, and radiology formed the second group, and the third group was composed of specialists from the fields of general and visceral surgery, internal medicine, and radiology. Informed consent was obtained from study participants individually prior to initiation of testing.

Selection of Cases

We used specific medical cases for our study, focusing on metastases in the liver. The only inclusion criterion was the presence of 1 or more liver metastases as well as having undergone an MRI scan of the liver in preparation for surgery or further diagnostics. These MRI scans served as the basis for the segmentation and development of the 3D image. Case selection was performed retrospectively, in cooperation with the departments of general and visceral surgery and radiology, resulting in a total of 5 cases. Five MC questions were created for each of the 5 individual patient cases, resulting in a questionnaire of 25 MC questions. The questions developed

were related to the present anatomy and topographical features of the patient's liver ([Multimedia Appendix 2](#)). Per case 2, MRI sequences were selected to use for answering the questionnaire. These sequences contained T1-weighting as well as T2-weighting in 4 of 5 cases. One case contained only T1-weighting but with 2 different sequences.

Statistics

The descriptive analysis included the calculation of means, medians, and SDs related to participant characteristics, calculation of correct answers, and overall processing time per participant and condition. To test the data for normal distribution, the Shapiro-Wilke test was used. The normally distributed numbers of correctly answered questions were analyzed with a 2-way repeated measures ANOVA to show statistical differences. We used the method of imaging (MRI or VR) and the status of the participant (student, resident, or specialist) as the dependent variables. The processing time was defined as the total time required to answer the questionnaire. To calculate the total processing time, the time needed to answer all questions of the questionnaire regarding all 5 cases was added. The processing time data also were analyzed with a 2-way repeated measures ANOVA. We performed a missing data analysis, which showed that there were no missing data to account for.

For the data of the adapted SUS and the 6 questions pertaining to the general benefit of the VR system, the modus and the minimal and maximal values were calculated. All statistical tests and graphics were performed and created with SPSS Statistics (version 28.0.1.0; IBM Corp). All raw data are available in [Multimedia Appendix 3](#).

Ethical Considerations

The medical ethics committee of Carl von Ossietzky University accepted this study (application 2021 - 162). The study was registered with the German Register of Clinical Studies (DRKS). Furthermore, we have committed ourselves to act according to the guidelines of the "Declaration of Helsinki" regarding the ethical principles for medical research on humans during the study. All participants signed a declaration of consent regarding participation. We followed the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guidelines when preparing the paper ([Checklist 1](#)). The selected image materials originated from patients of the Pius Hospital Oldenburg; the permission was obtained in the context of the consent of the patients. Participation of the participants was voluntary without given compensation. Before inclusion in the study, participants received detailed information about the study. Participants could withdraw from the study at any time without providing a reason and without facing any disadvantages. In the event of withdrawal from the study, data already obtained would either be destroyed or included in the study after inquiry as to whether the person agrees to the data being analyzed. This meant that the study participants had the right to have their data deleted if they withdrew from the study. The general abovementioned conditions regarding the handling of the collected data applied. All data were anonymized.

Results

Participant Characteristics

A total of 63 participants participated in our study. The participants were divided into 3 different groups. We categorized the participants as students, residents, and specialists of the departments of surgery, internal medicine, and radiology. In detail, we included 8 resident surgeons, 6 residents from internal medicine, 1 resident of the department of radiology. In the group

of specialists, we included 10 surgeons, 2 specialists of the department of internal medicine, and 1 specialist of the department of radiology. In total, we included 34 students (Multimedia Appendix 4).

In percentage terms, the proportion of female participants is higher in the student group than in the other defined groups (students: n=25, 71%; residents: n=8, 53%; and specialists: n=2, 15%). There is also a wide range in age as well as years of experience, especially in the specialist group (mean age 45.6, SD 9.18; range 33-61 years; Table 1).

Table 1. Participant characteristics.

| | Students | Residents | Specialists | Total |
|---|-----------------------|------------------|-------------------|-----------------------|
| Participants (n) | 35 (34 ^a) | 15 | 13 | 63 (62 ^b) |
| Age (years) | | | | |
| Mean (SD) | 26.8 (2.74) | 30 (2.81) | 45.6 (9.18) | — ^c |
| Range | 23-32 | 27-37 | 33-61 | — |
| Sex, n (%) | | | | |
| Female | 25 (71) | 8 (53) | 2 (15) | 35 (55) |
| Male | 10 (28) | 7 (46) | 11 (84) | 28 (44) |
| VR^d experience, n (%) | | | | |
| Never | 24 (69) | 6 (40) | 7 (54) | 37 (59) |
| ≤5 times | 11 (32) | 9 (60) | 3 (23) | 23 (37) |
| 5 - 10 times | 0 (0) | 0 (0) | 1 (8) | 1 (2) |
| >10 times | 0 (0) | 0 (0) | 2 (15) | 2 (3) |
| VR sickness, n (%) | 1 (3) | 0 (0) | 0 (0) | 1 (2) |
| Experience (years) | | | | |
| Mean (SD) | 4.4 | 2.6 | 11.2 | — |
| Range | 4-5 ^e | 1-5 ^e | 1-27 ^a | — |

^aIncluded number of students.

^bIncluded number of participants.

^cNot available.

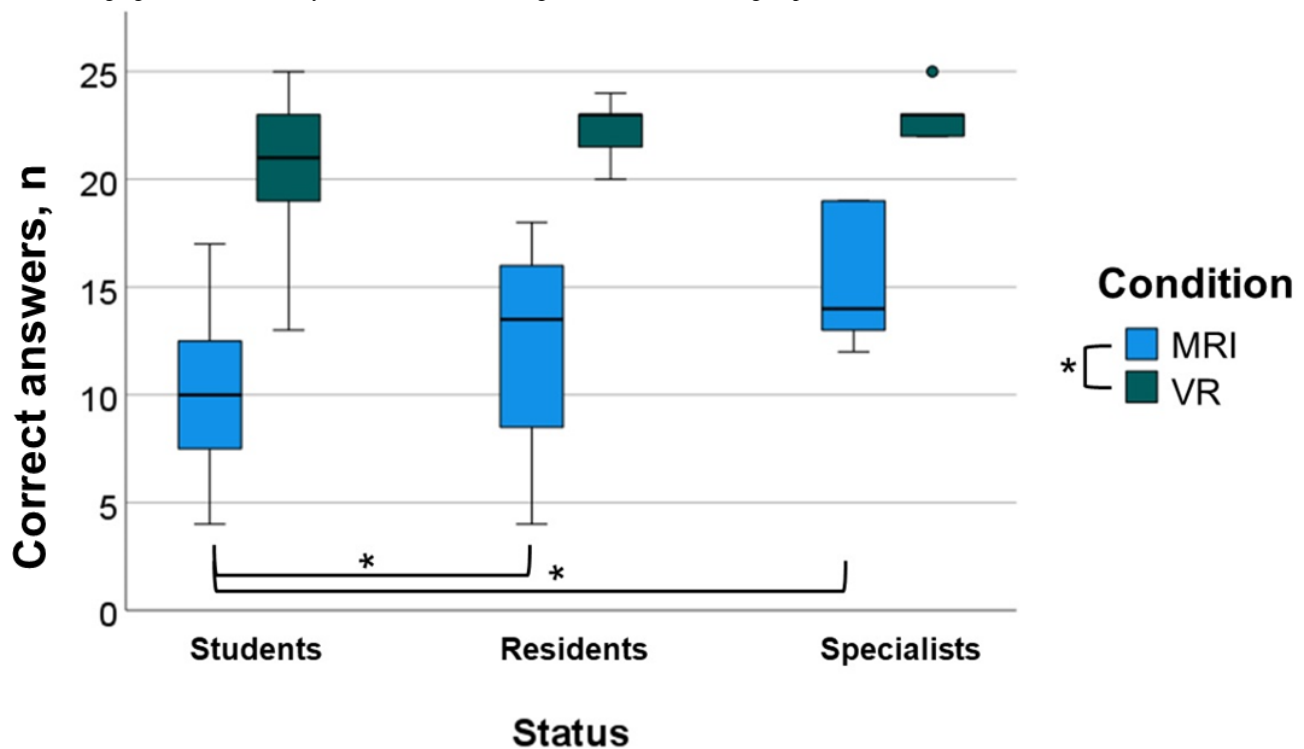
^dVR: virtual reality.

^eYears of experience regarding the group category.

There was also a wide range of experience of using VR. Overall, 24 students indicated they had never used VR, and 11 students indicated they had used VR 1 - 5 times. In the resident group, 6 participants had no VR experience, and 9 participants had used VR 1 - 5 times. A total of 7 specialists reported never having used VR, 3 specialists used VR 1 - 5 times, 1 noted use of VR 5 - 10 times, and 2 participants had used VR more than

10 times (Table 1). During the study, 1 student participant was excluded from the study due to VR sickness (Table 1). The mean of all participants showed an average of 11.8 (SD 4.19) correctly answered questions using MRI and 21.8 (SD 2.44) correct answers with additional use of VR technology (n=25; Figure 2).

Figure 2. Number of correct answers; comparing the different conditions (blue=MRI and green=VR) and contrasting the status (student, resident, and specialist). The box plot shows the median, the 2 quartiles, and the extreme values. The black circled dot indicates an outlier value. MRI: magnetic resonance imaging; VR: virtual reality. *indicates statistical significance between the groups.



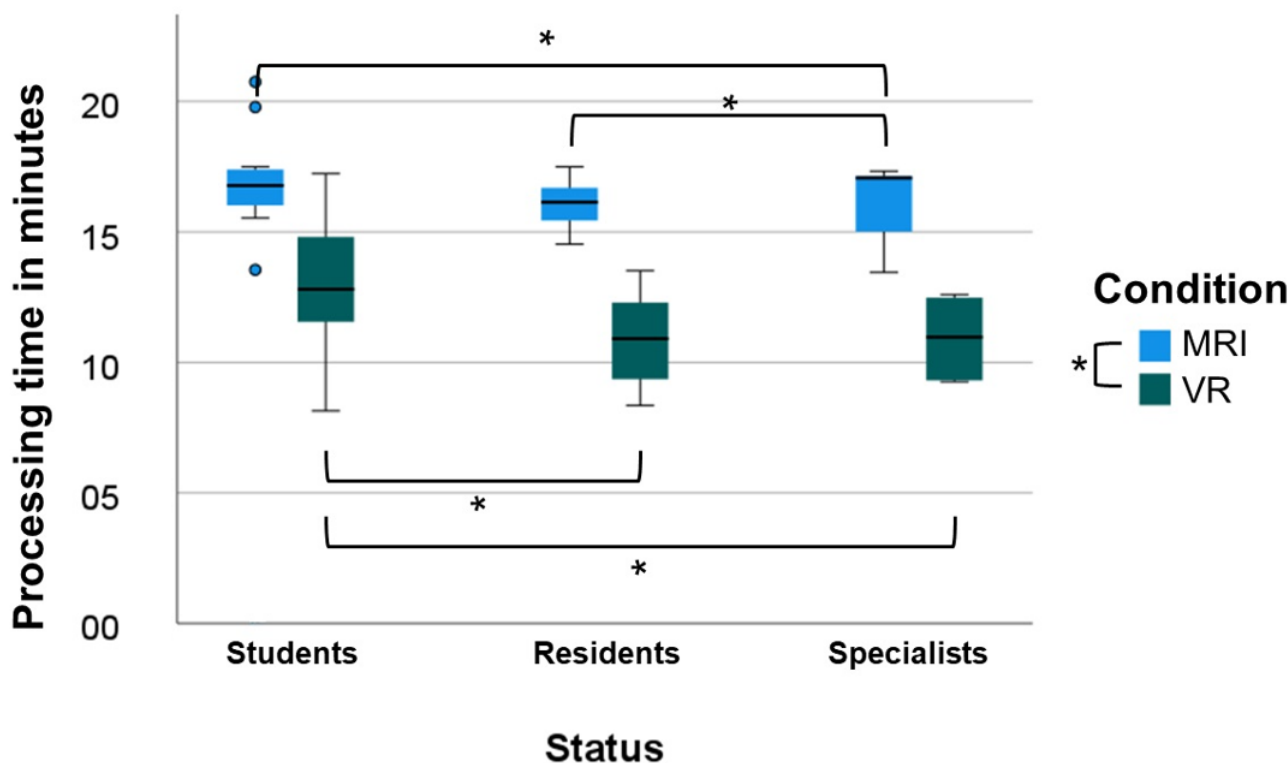
The multifactorial 2-way repeated measures ANOVA showed a significant difference in error rates between the MRI and the VR condition ($F_{1,59}=314.376$; $P<.001$) and an effect size of 0.842. Further, a significant interaction between condition and status could be presented ($P=.04$). In the pairwise comparison analysis performed for the MRI condition only, a significant difference was found between students and residents (students: median 10, IQR 7.25-12.75 and residents: median 13, IQR 10-16; $P=.04$) as well as between students and specialists (students: median 10 IQR 7.25-12.75 and specialists: median 14, IQR 13-18; $P<.001$). However, there were no significant

differences between residents and specialists (residents: median 13, IQR 10-16 and specialists: median 14, IQR 13-18; $P=.18$). For the VR condition, no significant differences between the sample groups can be shown (students: median 21, IQR 19.25-23; residents: median 23, 21.5-23; and specialists: median 23, IQR 22-23).

Processing Time

The analysis of the processing time showed an average processing time using the MRI diagnostics of 16.25 (SD 1.25) minutes. With the additional use of VR, the average value was 11.45 (SD 2.26) minutes ($P=.001$; Figure 3).

Figure 3. Processing time in minutes; comparing the different conditions (blue=MRI and green=VR) and contrasting the status (student, resident, and specialist). The box plot shows the median, the 2 quartiles, and the extreme values. The black circled dot indicates an outlier value. MRI: magnetic resonance imaging; VR: virtual reality. *indicates statistical significance between the groups.



The multifactorial 2-way repeated measures ANOVA showed a significant difference in error rates between the MRI and the VR condition ($F_{1,59}=280.700$; $P<.001$) and an effect size of 0.826. Furthermore, a significant interaction between condition and status could be presented ($P=.04$). In the pairwise comparison analysis, there was a significant difference in the processing time using MRI diagnostics between students and specialists (students: median 16.46, IQR 16.04-17.24 minutes and specialists: median 15.12, IQR 14.16-17.04 minutes; $P=.02$) as well as between residents and specialists (residents: median 16.54, IQR 15.43-17.27 minutes and specialists: median 15.12, IQR 14.16-17.04 minutes; $P=.047$). No significant results emerged between residents and students ($P=.33$).

Using VR, significant effects emerged between students and residents (students: median 12.44, IQR 11.25-14.42 minutes

and residents: median 10.52, IQR 9.21-12.00 minutes; $P=.004$) and students and specialists (students: median 12.44, IQR 11.25-14.42 minutes and specialists: median 9.19, IQR 8.36-12.32 minutes; $P=.02$). No significant differences were found between residents and specialists in the analysis ($P=.72$).

System Usability

The analysis of the VR system usability was assessed by an adapted SUS. The analysis was carried out based on group. The general acceptance of the system was good in every dimension of the adapted SUS in all groups (Table 2; Multimedia Appendix 5).

With regard to the questions about benefits and problems with both conditions, all groups gave similar answers, which were in favor of the VR condition (Table 3).

Table . Answers to the questions about general problems and benefits of the virtual reality conditions.^a

| Question | Students, mode (range) | Residents, mode (range) | Specialists, mode (range) |
|--|------------------------|-------------------------|---------------------------|
| Fun factor | 7 (5-7) | 7 (6-7) | 7 (4-7) |
| Amount of learning needed before using | 1 (1-5) | 1 (1-2) | 2 (1-5) |
| Feeling safe using | 5 (2-7) | 6 (3-7) | 6 (4-7) |
| Cumbersome handling | 2 (1-3) | 1 (1-2) | 2 (1-5) |
| Quick to learn technique | 7 (3-7) | 7 (3-7) | 5 (5-7) |
| Easy to use | 6 (4-7) | 7 (5-7) | 6 (4-7) |
| Unnecessary complexity | 2 (1-4) | 1 (1-3) | 2 (1-3) |
| Option of regular use | 7 (3-7) | 6 (5-7) | 6 (5-7) |

^aThe values for each question and each group are on a scale of 1=completely disagree to 7=completely agree.

Table . Answers to the questions about general problems and benefits of the VR^a and MRI^b conditions.^c

| Question | Students, mode (range) | Residents, mode (range) | Specialists, mode (range) |
|---|------------------------|-------------------------|---------------------------|
| VR can be a useful additional diagnostic tool | 7 (5-7) | 7 (6-7) | 7 (4-7) |
| VR is too complex for everyday clinical use | 2 (1-5) | 2 (1-6) | 2 (2-6) |
| VR can be a beneficial teaching tool | 7 (5-7) | 7 (6-7) | 7 (5-7) |
| VR helped to better understand the topographical conditions | 7 (5-7) | 7 (6-7) | 6 (5-7) |
| With VR, I was able to answer the questions with certainty | 6 (3-7) | 5 (5-7) | 6 (1-7) |
| With MRI, I was able to answer the questions with certainty | 2 (1-6) | 2 (1-5) | 2 (1-5) |

^aVR: virtual reality.

^bMRI: magnetic resonance imaging.

^cThe values for each question and each group are on a scale of 1=completely disagree to 7=completely agree.

Discussion

Findings, Objection, and Comparison to Prior Work

Our study focused on the usability of an additional use of 3D technology in a VR simulation for medical diagnostics to improve the visualization of anatomical structures and pathological findings. We assessed the usefulness of the VR technology as an additional tool in the medical field through an interindividual comparison. Participants were grouped according to their level of medical training and answered 25 MC questions first using sectional imaging (MRI) in a 2D environment (computer screen) and afterward with the respective segmented 3D model in a VR simulation. The main criteria were the number of correctly answered questions and the processing time. Secondary analyses were regarding the usability of VR technology using the SUS. The analysis showed that with the additional use of VR, there was a significant improvement in both main criteria as well as in the subjective perception that the questions were easier to answer in VR.

These results are especially important in light of the essential aspects in medicine, which include the knowledge of anatomical structures, the recognition of pathologies, the establishment of an appropriate diagnosis, and the indication of therapies [2-4,25]. Imaging procedures often play a decisive role in this context. In particular, the evaluation of MRI images is not always easy, as a cognitive transfer from a sectional image that is normally viewed in a 2D environment must be extended to a 3D environment. This mental transformation often correlates with the user's experience [2,3,22,25-27]. This inductive study was intended to examine the potentials of VR technology in the assessment of liver metastases compared to MRI across different levels of medical experience.

Our study demonstrated that the additional use of VR resulted in a significant improvement in the number of correctly answered MC questions and a reduction in the error rate across all groups. There was an average improvement of approximately 85% compared to using MRI alone.

Students performed significantly worse in answering the questions using MRI alone compared to residents and specialists. However, with the additional use of VR technology, this difference can no longer be shown. Thus, in this study, the student level is raised to that of a resident or a specialist. These results were achieved despite most students had little to no experience with the use of VR technology compared to the residents and specialists. Similar results were shown by Weyhe et al [18]. This can be interpreted as a statement of the quick and easy-to-learn handling as well as an understanding of VR technology, as also described by Schlegel et al [28].

Regarding the processing time, the additional use of VR technology results in a reduction of the average time needed of around 29%. These findings indicate that using VR technology has the potential to facilitate faster anatomical learning [15].

Further detailed analyses showed that both students and residents differ significantly from the group of specialists in the processing time using MRI to answer the questions. However, compared with each other, there is no significant difference between students and residents. This suggests that a high level of prior experience is required for the use of MRI as a diagnostic tool, as is evident in daily clinical practice and also shown by Nasi-Kordhisht et al [29]. In VR, there is a significant difference in the average processing time between students and residents, but no further significant difference between the group of residents and specialists. This seems to reflect the improvement of residents to a specialist level. Although the average processing time in the student group improved, the improvement was not statistically significant. The statistically nonsignificant difference could be attributed, among other things, to the small sample size or by a lack of clinical experience. Residents as well as specialists face the necessity of recognizing and working out the anatomy daily so that a more precise understanding might be created in a shorter time with the additional use of a 3D illustration [2,6,28,30]. Likewise, the students' nonsignificant improvement may be due to less experience with VR [6]. Furthermore, initial experiences with VR technology can be overwhelming, and to experience it, a new "reality" must first be processed. In addition, there might be a possible

playfulness as a student to try new things, which could distract from the actual task. Further, as shown by Walter et al [31,32], there could have been a certain skepticism toward an unknown technology [31,32]. In this case, having experience with VR and being experienced in the field of targeted diagnostics can have a positive effect.

As a secondary objective, all participants were asked about their satisfaction with the use of VR through a well-tested questionnaire, the SUS [23]. Here, a clear endorsement toward the use of VR could be shown. Aside from pure usability, subjective benefits showed up in the areas of simple learning, topographic understanding, and subjective security in answering the questions [15,28,33,34]. Additionally, a high fun factor was indicated [18]. Further, VR is seen as a benefit in clinical teaching as well as a future additional tool for diagnostics [30,33-37]. However, many respondents stated during our study that VR still seems too costly and too elaborate for everyday clinical use.

Regarding VR sickness, our study found minimal relevance. Among a diverse group of participants, which included different sex and age groups, only 1 participant showed mild symptoms most likely caused by VR sickness. This therefore affects about 2% (n=1) of our participants, which is a considerably lower value than reported in comparable studies [38].

The potential integration of VR into everyday clinical practice warrants evaluation. Nowadays, the gold standard in diagnostic imaging continues to be segmental (2D) diagnostics using MRI and CT [5]. Integrating VR would require several changes regarding acquisition costs, premises, integration into everyday life, and ethical and legal issues [39]. Furthermore, there is a need for further improvement in the creation of the virtual 3D representation in terms of time and personnel constraints so that this technology can be integrated into the clinical routine in a simplified way. Finally, the acceptance of the new technology by hospital staff is also pending [31,32,38]. In principle, it seems further basic research is also required in this area.

In our study, the transfer of conservatively learned anatomical knowledge to complex clinical aspects was investigated. It can be concluded from the different results that by using VR, an improvement of the transfer of the learned knowledge to clinical situations is possible. This can be explained by a possible simplification of topographical understanding through additional 3D presentation [16,36,40]. Another reason might be that in VR imaging, certain anatomical details can be displayed significantly better or only seen in VR [36,37]. With enhanced visualization of the anatomical structures, an improved anatomical and topographical understanding occurs, especially with a mismatch between learned anatomy and existing anatomical variations of an individual patient. Here, VR technology is a useful tool to highlight these potential differences in the preparation of an intervention by enhancing the representation of the actual anatomical situation, as shown by Pommert et al [14] and McDonald and Shirk [36]. In addition, Zawy Alsofy et al [41] demonstrated the practical benefits of this enhanced visualization by using VR technology for more accurate surgical planning and comparing it to using conventional imaging alone. Taking into account comparable

studies that include cognitive load theory with an impact on the learning process in these studies, it can be stated that the use of VR can reduce the cognitive load and thus may have a positive effect on the result [10,20,21].

In general, these results are difficult to compare due to the few similar studies available. However, the study results suggest that additional 3D technology could have a significant effect on the understanding of anatomical features and could improve clinical diagnostics and planning of treatments and surgeries [15,30,33-37,41,42].

Limitations

Regarding the limitations of our study, several issues arise. First, the restriction in the comparability with other studies and thus the difficulty of generalizing the data become apparent. The field of VR and clinical practice is explored in many studies; however, most of the studies also have an explorative character. In addition, hardly any study compares different professional groups and in particular the comparison between participants at different stages of medical training and the change in the respective level in relation to their level of training. This is the reason why it is challenging to refer to generally valid data in this study regarding this specific topic.

Second, our study was conducted at a single German university hospital, so the generalizability to other hospitals and other countries cannot be verified with certainty. On the other hand, the fact that all participants are from the same hospital and the same health care system, with a Germany-wide standard, also provides a good basis for data collection. Due to a Germany-wide standard, we believe that the findings can also be transferred to other hospitals in Germany. The international comparison still needs to be investigated further. However, due to similar working conditions with everyday time stress and employees with different levels of education and training as well as the same learning curves for MRI diagnostics, we also expect similar results in an international comparison.

Third, it should also be mentioned that no standardized MC questionnaire was used. Thus, the used tests lacked established values for quality criteria such as reliability and validity. However, based on the significant differences demonstrated between the groups in our study, the questions we used seem to be appropriate to highlight a difference between 2D visualization and VR. Further, the study results show only minor ceiling or floor effects.

Fourth, only certain MRI sequences were provided for answering the MC questions, so that the participant could not access the full potential of MRI diagnostics. This limitation had to be done for time management reasons and reflects a common clinical practice in many medical departments. Nonetheless, the most suitable sequences were selected in cooperation with the department of radiology.

Fifth, the time constraint for answering the questions, especially in MRI, may have led to a reduction in the number of correctly answered questions. Questions not answered in time were scored as incorrect. Increasing the time available could potentially improve the rate of correctly answered questions when using the MRI alone. On the other hand, time pressure is constantly

present in clinical practice, making this a test of VR's practicality.

Sixth, an observed improvement of the participants during VR use can partly be explained by a learning effect. In general, however, the effect presented here is strongly significant, so a sole learning effect cannot be argued as the sole cause. Furthermore, cases from everyday clinical practice were used, which could possibly be remembered by physicians, thus creating an advantage. Nevertheless, if the magnetic resonance images were already known, a significant improvement with the VR condition was still achieved.

Finally, the participant collection shows an imbalanced distribution in the groups; in addition, our design does not include randomization. This influences the results to a certain extent. However, due to the heterogeneous group of participants, especially due to the number of specialists, randomization or grouping was ruled out. The decision to use a cross-over design gave us the opportunity to have an adequate study size with a good database for analyzing the results. Another main reason for not using randomization was to investigate the interindividual comparison. The main aim of this study was not

to compare the usefulness of MRI versus VR; we wanted to show how the additional use of VR affects the understanding and use of knowledge for each participant, so we did not randomize. In addition, pretests have shown a higher recognition of cases when VR was used first. Here, participants quickly recognized the associated MRI. Conversely, there was a lower recognition value when MRI was used first. This was also one of the reasons for not using randomization.

Conclusions

The additional use of VR showed a significant improvement in the outcomes regarding correctly answered questions and general processing time across all groups. When transferred to the clinical routine, the add-on use of VR may enhance diagnostic accuracy. This, among other improvements, can be seen in the groups that already had clinical experience. This is also shown in the processing time, so the use of VR may lead to saving time. Both are components in medicine and in daily clinical routines that are of utmost importance for the adequate care and treatment of patients. In general, we see promising future benefits of 3D and VR technologies regarding anatomical understanding and surgical planning.

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Data Availability

All data analyzed during this study are included in this published paper and in [Multimedia Appendix 5](#).

Authors' Contributions

Conceptualization: JP, VU, DW, NT

Data curation: JP, VU

Formal analysis: JP, VU

Funding acquisition: DW

Investigation: JP, VU

Methodology: DW, NT

Project administration: VU

Resources: DW

Supervision: DW, NT

Writing – original draft: JP

Writing – review & editing: All authors

Conflicts of Interest

None declared.

Multimedia Appendix 1

Walkthrough the virtual reality simulation video.

[[MP4 File, 6525 KB - xr_v1i1e60383_app1.mp4](#)]

Multimedia Appendix 2

Questionnaire 1: multiple-choice questions (English).

[[DOCX File, 20 KB](#) - [xr_v1i1e60383_app2.docx](#)]

Multimedia Appendix 3

Raw data system usability scale and raw data magnetic resonance imaging or virtual reality.

[[XLSX File, 11794 KB](#) - [xr_v1i1e60383_app3.xlsx](#)]

Multimedia Appendix 4

Questionnaire 2: participant personal data (English).

[[DOCX File, 45 KB](#) - [xr_v1i1e60383_app4.docx](#)]

Multimedia Appendix 5

Questionnaire 3: system usability scale (English).

[[DOCX File, 16 KB](#) - [xr_v1i1e60383_app5.docx](#)]

Checklist 1

STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) reporting guidelines checklist.

[[DOCX File, 34 KB](#) - [xr_v1i1e60383_app6.docx](#)]

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Abbreviations

CT: computed tomography

MC: multiple-choice

MRI: magnetic resonance imaging

STOBE: Strengthening the Reporting of Observational Studies in Epidemiology

SUS: system usability scale

VR: virtual reality

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Original Paper

Virtual Reality for Basic Life Support Training in High School Students: Thematic Analysis of Focus Group Interviews

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Abstract

Background: High-quality and engaging cardiopulmonary resuscitation (CPR) training of both health care professionals and members of the public is necessary to provide timely and effective CPR to maximize survival and minimize injuries. Virtual reality (VR) is a novel method to enhance CPR engagement and training. However, a near-peer mentoring framework has not been applied in such training to date.

Objective: The purpose of this pilot qualitative study was to understand the acceptability and feasibility of using VR technology to introduce basic life support (BLS) to high school students reinforced by near-peer coaching.

Methods: Dyads of high school students underwent BLS training in CPR using a VR experience reinforced by the near-peer mentoring model. Focus group interviews were performed following the intervention. The interview sessions were recorded, transcribed verbatim, and subjected to thematic analysis. VR software data were analyzed after five cycles of chest compressions between the two participants.

Results: The overwhelming responses from the three dyads of high school students indicated positive acceptance of learning CPR using VR. Analysis of emerging themes revealed three main categories of barriers and facilitators: (1) motivation to learn CPR, (2) CPR learning modality, and (3) coaching CPR content. These themes supported the theoretical framework of an "intention-focused" paradigm leading to acquiring the skills needed to perform CPR and ultimately increasing the chances of a bystander performing CPR.

Conclusions: This study highlights the potential for training a unique population to increase bystander effects using novel VR technology coupled with a near-peer mentoring method. Further research is warranted to measure the outcome of the knowledge attained and the intention to perform CPR by high school students who participate in CPR education using VR and a near-peer mentoring method.

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KEYWORDS

virtual reality; mixed reality; technology; basic life support; cardiovascular pulmonary resuscitation; near-peer mentoring; education; high school students

Introduction

Sudden cardiac arrest (SCA) is an uncommon phenomenon in youth; however, according to the Centers for Disease Control

and Prevention, approximately 2000 healthy people under 25 years of age in the United States die each year due to SCA [1]. Regardless of one's age, the survival odds of SCA outside of a hospital setting are low, which is likely related to the low

bystander cardiopulmonary resuscitation (CPR) rates [2,3]. Therefore, it is important to increase the general public's awareness and knowledge levels of CPR to consequently increase the number of bystanders who may initiate CPR in an emergency situation [4]. Educating and engaging adolescents in life-saving maneuvers such as CPR is a crucial step in increasing the lifelong ability and motivation to take actions in an emergency [5,6].

High-quality and engaging CPR training of both health care professionals and members of the public is necessary to provide timely and effective CPR to maximize survival and minimize injuries [7]. Traditionally, CPR training has occurred in an in-person group setting utilizing CPR mannequins. Due to the COVID-19 pandemic, this traditional approach of CPR training shifted toward a focus on smaller group sizes to minimize hands-on simulation activities. Virtual reality (VR) is a novel method to enhance CPR engagement and training, which has shown rapid growth since 2019 [8,9]. The immersive VR training induces a greater sense of presence and agency when compared to traditional CPR training, and may be more effective in increasing the intention and initiative to perform CPR in real-world emergencies [10]. Such VR technology enhancements have been particularly well received by the "technology natives" of the younger generation [11]. A systematic review identified the current gap of this field as the lack of educational programs rated at 3-4 on the Kirkpatrick model, which is a method of evaluating the results of training and learning programs [12]. This highlights the importance of continued development and improvement in simulation education, particularly in the context of CPR training. While there is a growing interest in leveraging novel technologies for CPR training, few studies have assessed their potential [13].

Near-peer mentoring is a learner-centered model, where the pairing of mentors and mentees close in age and developmental stage allows for mentors to draw on personal experiences to connect with mentees. This facilitates connections and reflections integral to the experiential learning process [14]. However, the relationship between CPR training and use of VR technology based on a near-peer mentoring framework has not yet been investigated, particularly in the high school population.

To fill this gap, our primary objective was to assess the feasibility of VR technology as a novel learning modality for CPR training and to apply the near-peer mentoring model in this CPR training among adolescents. Toward this end, we evaluated the relationship between the following three domains: CPR, VR, and near-peer mentoring. Our secondary objective was to collect and document the lived experiences of adolescents upon experiencing VR to obtain basic skill sets associated with CPR.

Methods

Recruitment

High school students were recruited from participants of Camp Children's Hospital Los Angeles (CHLA), which is an annual,

week-long health care career exploration summer camp for high school students between 15 to 17 years of age in Los Angeles County. The VR-based CPR sessions were offered as a voluntary option. The study was conducted in the Las Madrinas Simulation Center at CHLA.

The target number of participants to recruit for this qualitative pilot study was not established a priori. According to Creswell [15], between 5 and 25 interviews for phenomenological studies were reported to be appropriate. In addition, Morse [16] specified recruiting at least 6 participants for phenomenological studies. Neither of these studies included the rationale for the indicated numbers.

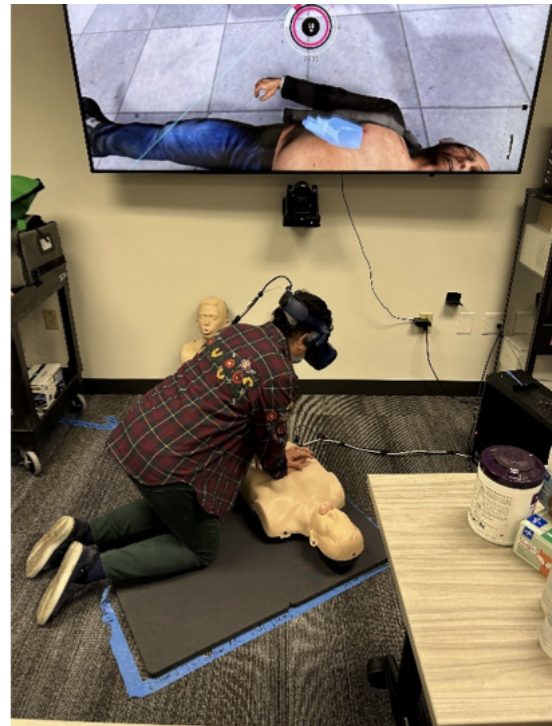
Ethical Considerations

The protocol and participant-facing materials underwent review by the CHLA institutional review board, and approval was obtained prior to any data collection (case number CHLA-22-00230). Informed consent and assent were obtained from the identified participants and their respective parents prior to the day of the study. Participants were not offered compensation. Consents and assents were electronically obtained via the Research Electronic Data Capture (REDCap) system where corresponding participant IDs were created. The identifiers were removed during the transcription process and the recordings were destroyed once transcription was completed.

Data Collection

Dyads of high school students underwent CPR training using a VR-based hybrid simulation platform (CBS, TetraSignum). Prior to the VR session, each dyad watched approximately 30 minutes of didactic content delivered by a virtual avatar instructor. Following the didactic portion, the students took turns and had an opportunity to perform hands-on CPR on a quality CPR (QCPR) mannequin. Next, the VR software data, which scored five cycles of chest compressions between the two participants, were analyzed. We used a Vive Pro (HTC) hardware system, which enabled simulcasting the VR user's view to a screen for others to watch. The VR software superimposes a virtual avatar over the location of the mannequin to simulate a human in cardiac arrest. This QCPR technology uses wireless sensors embedded in the mannequin to measure the effectiveness of core CPR components [17]. The steps of the CPR consisted of (1) a check response, (2) a call for help, (3) a check for breathing, (4) five cycles of chest compressions and rescue breaths, and (5) using an automated external defibrillator. This experience was reinforced by the near-peer mentoring model as a pair (Figure 1). The sessions were immediately followed by approximately 45 minutes of focus group interviews led by the research team. The debrief interview sessions used open-ended questions addressing the domains of interest and the participants' lived experiences. The interview sessions were recorded, transcribed verbatim, and analyzed.

Figure 1. Dyads of campers underwent basic life support training using a virtual reality–based hybrid simulation platform.



Phenomenology

Phenomenology is a type of a qualitative research method with roots in psychology and philosophy. Phenomenology is best applied to understand the lived experiences of individuals where the focus is exploring [18,19]. In our study, participants interested in a career in health care intentionally chose the VR CPR tract as part of their day. Accordingly, this study aimed to gain insight as to “how individuals make sense of the world to provide insightful accounts of their subjective experience” [18], and to gain understanding of the phenomenon of introducing the contents of basic life support (BLS) and CPR using VR and near-peer mentoring to high school students.

Data Analysis

The interview sessions were recorded and transcribed verbatim. An interdisciplinary team of medical researchers used a thematic analysis approach as described by Braun and Clarke [20]. The first three authors (HJM, CA, and ROLBB) read the transcripts to understand the students’ perceptions and acceptability of using VR to learn CPR with a near-peer mentoring model. Next, the transcripts were coded systematically across the three team members and combined for reflexive thematic analysis [21]. The three research team members, including two research nurses (HJM and ROLBB) and a physician (CA), analyzed the focus group data using constant-comparison analysis. This approach allows for richer interpretations of meaning, particularly across multidisciplinary research members. Constant comparison also allowed for refining, defining, and naming themes. Once codes were created, they were grouped into barriers and facilitators, and then broader themes were identified by circling back to the near-peer mentoring model and the intersection between VR

and CPR. Finally, the thematic auditors (DRL and TPC) reviewed the identified themes for any discrepancies.

Results

Recruitment

This pilot study launched over the summer of 2022. We recruited a total of three dyads of 6 high school students from a total of 31 students participating in the CHLA camp. The parents of the 6 participants provided consent and individual participants provided assent to be interviewed to share their lived experiences of learning CPR using VR and acting in the role of “coach” based on the near-peer mentoring model. The cohort comprised 2 boys and 4 girls with a mean age of 16.5 (range 15-17) years. Of note, this was the first on-site camp since the COVID-19 pandemic; therefore, there was a smaller total group of campers selected for that year, ultimately leading to a smaller sample size for this study.

Data Saturation

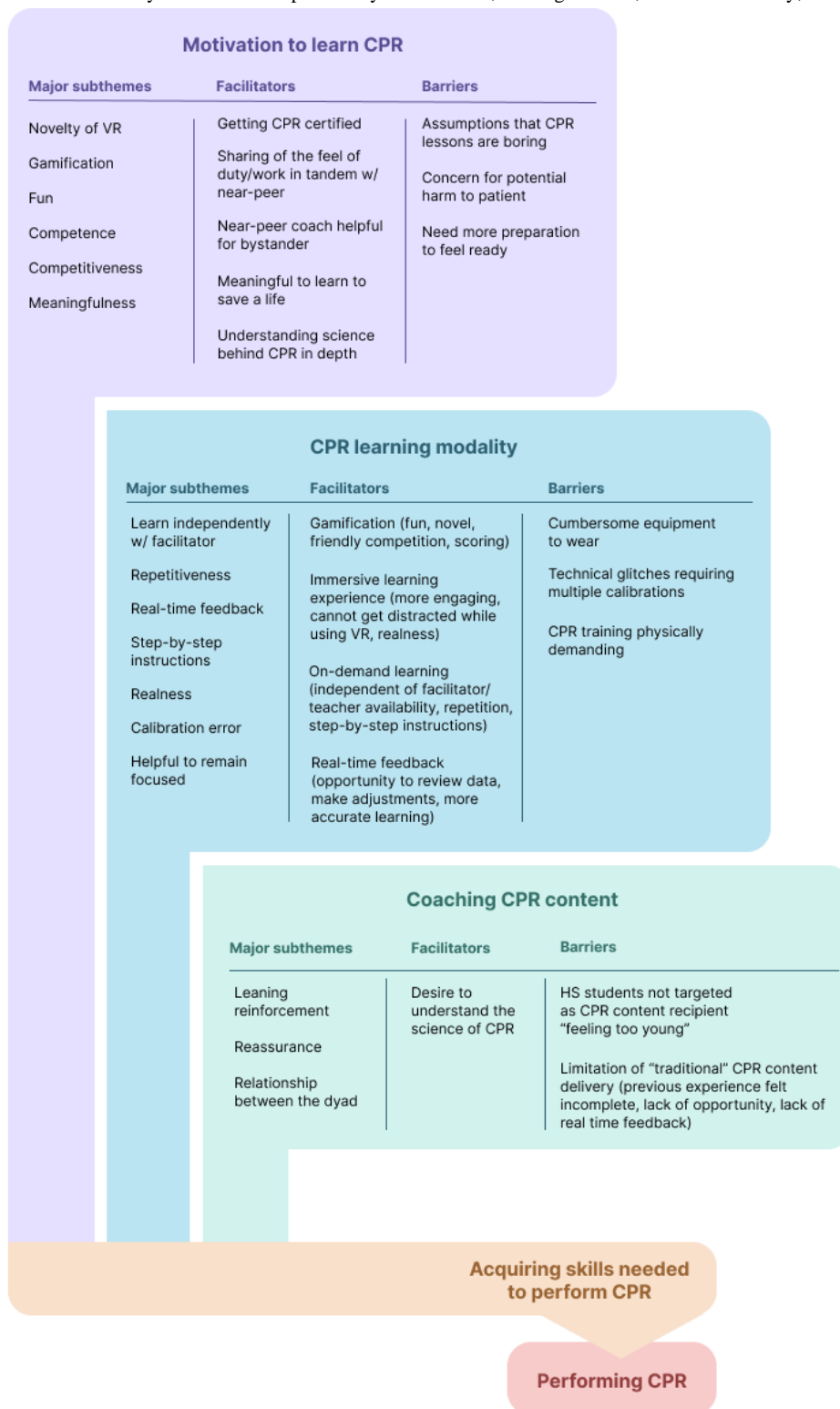
Data saturation in a qualitative study is defined as the collection of qualitative data to a point of “sense of closure,” because there are no new insights obtained and the data yield redundant information [19,22]. Attempts were made to have the campers return to campus after the camp had been completed; however, since the students were back at school, we were unable to recruit additional participants.

Themes

Main Themes Identified

During the qualitative analysis process, three themes were identified: (1) motivation to learn CPR, (2) CPR learning modality, and (3) coaching CPR content (Figure 2).

Figure 2. Summary of the thematic analysis. CPR: cardiopulmonary resuscitation; HS: high school; VR: virtual reality; w/: with.



Motivation to Learn CPR

Motivation to learn CPR was defined by themes arising from the individuals’ expressed extrinsic and intrinsic motivation to learn. Participants reported the novelty of VR and the engaging space of the simulation center to be a motivating factor in learning CPR. Our method of learning was unique when compared to the traditional method of a CPR class and its preconceived notions because it created “a more engaging space

for kids to be more interested in CPR.” Furthermore, the gamification of learning by VR was considered to be fun, and even peers who may not have an interest in health care would also be interested since VR would “automatically assumed to be fun because it’s a game.” The final scores provided by the software served as positive feedback of competence and elicited competitiveness as a source of encouragement in the participants’ ability to achieve success. Lastly, many of the

participants reported that it was meaningful to be able to learn how to save a life.

CPR Learning Modality

The learning modality of CPR was defined by themes arising from the method, medium, or delivery of the CPR learning via VR and peer coaching. The participants reported that being able to learn independently without having a facilitator or teacher supervision would allow them to repeat the learning process at their own pace (eg, “you keep practicing, eventually it’ll become second nature”) and that when faced with an emergency, one would feel more prepared to assist. The real-time feedback from the avatar trainer and the in-person peer coach was considered to be helpful. In addition, the ability to address concerns such as “Are we going at the right pace?” “Are we going too slow?” “Is the pressure right?” on a real-time basis enabled immediately making changes and adjustments in real time as needed. The step-by-step instructions helped to reinforce the knowledge. One camper shared, “I like that it went step by step because it helped to absorb the information easier.” There was also feedback regarding the avatar often moving out of sync with little or no time for the participant to reflect. For instance, “it was like after you finish check response and then he just quickly moved on to the next one. Maybe just a little bit time to reflect...” Lastly, the realness of the VR simulation and tactile hands-on learning modality helped participants to be better prepared when compared to the traditional lecture-based or passive online modules: “I liked it was more accurate. I like that it put me in a real-life situation and, I felt like it made me more prepared.” The participants also shared calibration error to be a source of distraction in learning, which occurred when the mannequin’s sensor and the participant’s hands were not calibrated correctly. Lastly, use of VR enabled the participants to remain focused while learning, because “you weren’t looking around or getting distracted by anything,” since while the headset is on, the participant is engaged in the “VR world” and is therefore unable to become distracted.

Coaching CPR Content

Coaching CPR content was defined by themes arising from the dyads’ experiences of serving as a coach and being coached as a pair. Although the pair started by watching the 30-minute introduction training videos together, many participants shared that being able to coach after having the opportunity to go through the program first helped them to feel more confident in coaching. The comments offered as a coach served as additional learning reinforcement, as stated by one participant: “whatever I said to her stuck in my mind, so I was able to remember that for when I went.” The presence of the coach also provided a sense of reassurance because participants “felt reassured like I wasn’t being pressured to do everything and then forgetting anything.” Working in tandem in CPR training impacted the pair’s perception of the responsibility of a “scary situation” to be less daunting. An important factor to be mindful in assigning of the pair was assessment of the relationship between the dyad:

If I had just met someone, maybe I wouldn’t be as comfortable telling them what to do or what not.

Probably just the relationship with people would be the biggest aspect of coaching.

Recommendations for Future Projects Provided by Participants

Helpful ideas for future iterations of the VR-based CPR trainings included adding options of different major metropolitan cities, background music, and personalization of avatars. Moreover, participants suggested expanding the trainings to include a pediatric population, ranging from infants to toddlers to school-aged children. Lastly, they suggested using a more seamless VR technology to impose less of a burden associated with the headset.

Discussion

Our findings show that it will be valuable to leverage the currently available VR technology to promote CPR education for high school students. Moreover, purposeful inclusion of a near-peer mentoring approach can have a synergistic contribution to the training and result in a positive learning experience. The themes identified in our study build upon the existing theoretical framework proposed by Panchal et al [23], termed the “intention-focused model for bystander CPR performance,” which allows gaining an understanding of the determinants of bystanders’ decision-making process. The proximal domains preceding the intentions start with the bystander’s demographic characteristics, including gender, age, personality traits, and education level. These baseline demographic variables then lead to their “beliefs,” categorized by “attitudes,” “perceived norms,” and “self-efficacy,” in performing CPR. These beliefs then result in the “intention” to perform CPR, bolstered by the “skills needed to perform CPR” as a determinant of behavior, which ultimately leads to the action of performing CPR.

Therefore, the themes unveiled from our qualitative data analysis were consistent with the intention-focused model for the bystander CPR performance framework. Our research design of phenomenology and documentation of the “lived experiences” of the participants expanded upon the demographic characteristics and beliefs associated with CPR prior to this new learning experience. The main purpose of this VR CPR project was to equip the participants with the knowledge and skills needed to perform CPR. The three major themes unveiled from our analysis add to the preceding themes leading up to the “skills needed to perform CPR” in the intention-focused model, which were (1) motivation to learn CPR, (2) CPR learning modality, and (3) coaching CPR content.

The motivation to learn CPR is a new domain that is distinct from the previously identified “attitudes,” “perceived norms,” and “self-efficacy” about performing CPR. Self-determination theory is a motivational theory of personality, development, and social process that examines how individuals are driven and depicts motivation on a continuum [24]. Notably, our participants were highly motivated individuals who are interested in future careers in health care. In accordance with the framework of Panchal et al [23], it will be important to introduce a moderating factor to motivate high school students

to be intrinsically motivated where the motivation's root stems from interest, enjoyment, and satisfaction.

The overwhelming positive feedback received by the participants in regard to learning CPR via VR is consistent with prior research showing a link between novelty and curiosity [11,25,26], where "when a novel stimulus affects an organism's [brain] receptors, there will occur a driving stimulus producing response called curiosity" [26]. Our novel approach to the learning and delivery of CPR content may have steered the "attitudes" and "perceived norms" about performing CPR in a positive direction. A scientific statement by the American Heart Association noted that novel methodologies and digital platforms (ie, gamified learning, social media, and crowdsourcing) do not necessarily improve response and performance; however, novelty allows for the potential to reach a larger population with various types of learners [27]. Likewise, although this pilot study did not measure the changes in the "intention to perform CPR," based on the feedback provided by participants, this approach has the potential to reach and create interest in high school students.

Since the VR CPR learning modality would allow for learners to repeat the learning sequences independently in their own time, as one participant stated, "if anything like this were to happen, you would be able to do it." A similar study from 2016 that evaluated multiplayer virtual training in medicine among 12 Swedish medical students found that virtual training may result in "erroneous self-beliefs" affecting future clinical practices [11]. This study points to the importance of future studies to measure the "intention to perform CPR" and assessment of the efficacy of VR-based training compared to traditional training methods [13].

There was a similar study evaluating the influence of near-peer mentoring in CPR workshops on medical students' knowledge and satisfaction [28]. Similar to the findings with our high school students, the previous study reported the benefits of this type of mentorship to be helpful in that the peers have similar levels of experience, and they are more familiar with the educational needs and better understand the learning process and potential areas for confusion [28].

The selection of inherently motivated high school students with career aspirations in health care may have posed a bias, thereby limiting the generalizability of the study, in addition to the small sample size of 6 participants. In addition, consistent with the design of this pilot study, it can be difficult to present generalizable findings of phenomenological research due to the highly individual records of lived experiences. Lastly, although we did not collect measures specifically evaluating changes in intentions to perform CPR in the future, previous studies have indicated that a bystander who had experienced CPR training was up to 6 times more likely to perform CPR when witnessing an out-of-hospital cardiac arrest [3,29,30]. Although outside of the scope and aims of this study, we did not collect any data to measure the quality of the CPR. Nevertheless, it is still meaningful that the students were trained on the sequences of BLS.

Our findings show that it is feasible to leverage a novel technology such as VR to enhance the CPR learning experience. Particularly for high school students, learning CPR using VR served as a source of motivation, which was fostered by the unique modality of learning in the presence of a near-peer coach. These benefits could contribute toward training a future generation who will be more confident to perform CPR as a bystander in an emergency situation.

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Data Availability

Data for this study, which comprise the transcription files and coding from the first 3 authors, may be made available upon request to the corresponding author.

Conflicts of Interest

None declared.

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Abbreviations

BLS: basic life support

CHLA: Children's Hospital of Los Angeles

CPR: cardiopulmonary resuscitation

QCPR: Quality CPR

REDCap: Research Electronic Data Capture

SCA: sudden cardiac arrest

VR: virtual reality

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Original Paper

Factors Associated With Risky Drinking Decisions in a Virtual Reality Alcohol Prevention Simulation: Structural Equation Model

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Abstract

Background: Risky alcohol consumption among adolescents is a significant public health concern in most Western countries. Various motives and factors (eg, sensation seeking, gender, reduced self-efficacy) known in the literature are associated with risky drinking decisions in real life. Efforts to tackle risky drinking decisions in real life through skills training to deal with social pressures have been successful. However, interventions of this nature require significant resources. Technological solutions, such as virtual reality (VR), offer advantages, as they enable immersive experiences that replicate real-life scenarios. However, a question persists pertaining to the fidelity of real-world behaviors within virtual environments.

Objective: This study is exploratory and aims to ascertain if the established drinking motives and factors for risky drinking decisions are transferrable to the virtual environment in the simulation game VR FestLab and to uncover determinants linked to risky drinking decisions within the simulation.

Methods: The study analyzed data from the intervention arm of a cluster-randomized study of 161 Danish students aged 14-18 years who tested the virtual alcohol prevention simulation VR FestLab. At baseline and before playing VR FestLab, independent variables such as age, gender, alcohol consumption, use of other drugs, sensation seeking, drinking refusal skills, knowledge of blood alcohol concentration, and refusal communication skills were recorded. The dependent variable, virtual risk decisions, was measured immediately after the gameplay. Confirmatory factor analysis and structural equation modeling were used to examine the latent variables in relation to virtual risk decisions. Moderation analyses for age and gender in relation to the latent characteristics and the primary outcome were also conducted.

Results: The data indicate that 73.9% (119/161) of the participants engaged in binge drinking at least once in their lifetime. The confirmatory factor analysis demonstrated a good fit of the items for their respective constructs; therefore, they were adopted without modification in the structural equation model. The data suggest that individuals with prior alcohol experience are 4 times more likely to engage in virtual risk decisions within the simulated environment (odds ratio 4.31, 95% CI 1.70-10.84; $P=.01$). Knowledge and awareness of blood alcohol concentration were associated with a lower chance to engage in virtual risk decisions (odds ratio 0.32, 95% CI 0.11-0.93; $P=.04$). However, no significant associations were found between virtual risk decisions and other latent variables. Gender and age did not moderate the associations.

Conclusions: The immersive and lifelike properties of VR partially reflected risk-related decisions. However, it remains unclear which factors favor the mapping of real-world behaviors in virtual simulations. Therefore, future research should address the mechanisms underlying behavioral dynamics in virtual simulations and explore the translation of virtual behaviors into real behaviors to gain a comprehensive understanding of the potential of virtual simulations for alcohol prevention.

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KEYWORDS

alcohol; prevention; virtual reality; risk behavior; structural equation model

Introduction

Alcohol prevention continues to represent a pertinent public health concern worldwide [1]. Despite witnessing a reduction on a global scale since the establishment of the Millennium Development Goals in 1995, alcohol consumption still contributes to 5% of disability-adjusted life years and 5% of total fatalities [2]. Furthermore, harmful alcohol consumption is pivotal in over 200 diseases and injury conditions [3]. Notably, alcohol prevention remains significant, particularly among adolescents, as indicated by the latest European School Survey Project on Alcohol and Other Drugs report, which reveals that approximately 80% of students aged 15-16 years have experimented with alcohol at least once [4]. Denmark surpasses the European average, with roughly 92% of adolescents having consumed alcohol at least once in their lifetimes [4].

To effectively deter premature substance use among adolescents, targeted alcohol prevention programs prove indispensable [5]. In this context, it is important to consider the motives underlying risky consumption patterns among adolescents. A systematic review conducted by Adan et al [6] revealed an association between risky drinking behavior and specific personality traits. For instance, binge drinking was correlated with increased impulsivity and sensation seeking [6], while Stautz and Cooper [7] and Percy et al [8] established an association between high sensation seeking and an increased likelihood of heavy episodic drinking. Other studies have identified binge drinking as particularly linked to male gender and reduced self-efficacy [9]. Moreover, engagement with other legal or illegal substances, apart from alcohol, correlates with increased risk behavior. Creamer et al [10] demonstrated that using various tobacco products corresponds to heightened risk behavior. Additionally, a correlation exists between cannabis use, drinking-related risk behavior [11], and the frequency of alcohol-related consequences [12].

Given the known drinking motives among adolescents, prevention programs anchored in concepts like inoculation theory [13] and social learning theory [14] advocate for skill enhancement that strengthens resilience against social influences, such as peer pressure for risky behavior. Research involving life skills training in educational institutions underscores the value of cultivating social resistance skills and broader personal and social competencies, leading to decreased cigarette use and enhanced anti-drinking attitudes [15]. Moreover, participants demonstrated higher substance use awareness and skill-related knowledge [15]. Effective refusal communication skills and risk-related knowledge are crucial

components for enhancing the personal and social skills of young people. Refusal communication, which involves the ability to say “no” to substance offers, is essential in reducing substance use and risky behavior. Several studies have demonstrated that individuals with strong refusal skills regarding alcohol misuse exhibit reduced abusive alcohol use [16-18], possess greater knowledge of alcohol misuse prevention, are less susceptible to peer pressure, and have better internal health control [19]. However, in addition to communication skills, it is also crucial for young people to have knowledge about substance use and its effects on the body to assess and avoid risks. Individuals with greater knowledge of substance-related topics may be better equipped to handle risky situations, potentially reducing the likelihood of substance abuse. Various studies have explored the relationship between substance-related knowledge and the reduction of risk behaviors, such as alcohol consumption. Teesson et al [20] conducted a cluster-randomized study in schools and found that combining digital prevention programs that increased alcohol-related knowledge resulted in a reduction in binge drinking. Hasking and Schofield [21] demonstrated that health and alcohol knowledge can strengthen the intention-behavior relationship. Individuals with more alcohol-related knowledge and experience are likely to be better informed about the consequences. Conversely, better-informed adolescents are likely to feel better prepared to minimize the risks of alcohol consumption [21]. Padget et al [22] discovered that increased awareness of the detrimental effects of alcohol on the brain resulted in improved perceptions of harm and subsequent attitudes of alcohol aversion. These improvements had a significant impact on the intention not to use alcohol, but they did not result in a significant reduction in short-term alcohol consumption. Therefore, it is important to note that knowledge about alcohol may be only one of many factors that can influence risk-taking decisions. Risk behaviors are frequently caused by multiple factors, and knowledge about alcohol may only have a partial impact on the development or absence of such behaviors.

Although traditional skills training involving rational alcohol consumption often relies on labor-intensive and costly in-person role-playing, contemporary technological solutions such as virtual reality (VR) have emerged. An intrinsic advantage of VR lies in its capacity to deliver an immersive encounter that faithfully mimics real-life scenarios. By replicating authentic situations, VR prompts participants to enact genuine behaviors within virtual environments [23,24]. Whereas studying real-world behaviors within experimentally controlled settings posed challenges, VR now allows one to scrutinize behaviors within genuine settings and uncover determinants of behavioral intentions [25].

The convergence between VR and real-life behavior might be attributed to presence and immersion. Individuals immersed in VR experiences can subjectively experience a sense of “being there” in the virtual realm. This sense of presence fosters more authentic and realistic behavioral responses akin to real-world conduct [26]. Alcañiz et al [27] reported that comparable neural mechanisms can be triggered in individuals immersed in a virtual world, paralleling experiences in the physical world. Additionally, the increasing realism and interactivity of VR technology play a role. As VR systems advance, they provide heightened sensory input and feedback, including lifelike visuals, haptic responses, and precise motion tracking. These immersive, lifelike elements contribute to greater congruence between VR and real-life behaviors [28]. Moreover, psychological factors such as social presence and adherence to social norms influence VR behavior, as people replicate real-world behaviors due to a sense of social presence and the desire to conform, even within virtual contexts [29].

The immersive, authentic portrayal of virtual environments implies that genuine risk behaviors are likely to manifest in these settings. This conjecture is supported by the findings that, for example, children exhibiting higher risk behavior in road traffic replicate this behavior in a virtual cycling simulation [30].

Nonetheless, reviews indicate that VR’s role in substance use prevention remains limited [31,32]. Thus, a cocreated virtual alcohol prevention simulation (VR FestLab) was developed in 2020 [33]. The VR FestLab application, an educational game simulation, aims to enhance the refusal self-efficacy of adolescents aged 15-18 years who experience social pressure to consume alcohol. Given the scarceness of VR-based alcohol prevention applications [31,32], this study was exploratory and aimed to ascertain if the established drinking motives and factors for risky drinking decisions are transferrable to VR FestLab. A structural equation model was used to uncover determinants linked to risky drinking decisions within the simulation. To this end, the following hypotheses were formulated for testing:

1. Higher sensation seeking is associated with increased virtual risk decisions in the simulation.
2. Enhanced knowledge and awareness of blood alcohol concentration (BAC), refusal communication skills, and drinking refusal skills are linked to reduced virtual risk decisions in the simulation.
3. Prior alcohol experiences are associated with increased virtual risk decisions in the simulation.

Methods

Study Design

The data were collected as part of a longitudinal study that investigated the efficacy of the VR FestLab application. The comprehensive procedure and outcomes of the primary study can be found elsewhere [34]. To achieve this objective, a total of 13 Danish schools were allocated in a 1:1 ratio to either the intervention or control group. The schools assigned to the intervention group engaged with the VR FestLab application, whereas those in the control group played the VR game First

Steps (Meta Platforms Inc). The data set in this study was derived from the 7 schools that were selected as intervention schools only. Data collection transpired within the school premises between August 2020 and December 2020 and then again from April 2021 to May 2021; the latter period was necessitated by COVID-19 restrictions. For the original study [34], a sample size calculation was performed using STATA 15 with a 2-sample *t* test. This resulted in a sample size of 135 individuals for the control group and 135 individuals for the intervention group to yield an intervention effect of Cohen $d=0.44$, with a power of 0.80 using a 2-sided α of .05. The sample size was calculated based on an estimated intraclass correlation for drinking refusal self-efficacy of 0.01 and 45 students per school. Taking into account an estimated attrition of 35%, 420 participants were planned to be recruited for the study. Further information can be found elsewhere [34].

Participants

To enroll adolescents aged between 14 and 18 years, initial contact was established with the administrations of the 7 schools through email. Once the school administrations granted their approval, the study’s objective was presented to the respective classes, emphasizing the confidential and anonymous nature of data collection. In accordance with the principles outlined in the Declaration of Helsinki, all students were duly informed that their participation was voluntary, and they gave written consent prior to their involvement.

Ethical Considerations

The study adhered to Danish standards for the ethical conduct of scientific studies and was approved by the Research Ethics Committee of the University of Southern Denmark in March 2020 (case no 20/5348; date of approval: January 22, 2020). In accordance with the Ethics Committee of the University of Southern Denmark, parental consent was waived, as it is only mandatory for adolescents under the age of 15 years in Denmark [35].

The Virtual Reality Simulation VR FestLab

The Danish VR application, VR FestLab, immerses users in a 360-degree filmed simulation and was specifically designed for adolescents aged between 15 and 18 years. A total of 128 distinct scenes allows users to engage with diverse simulation sequences. This interactive experience commences at the home of a school friend, where they both join in a birthday celebration. Within this simulation, users can navigate through 2 virtual rooms using eye movements. As they move within these spaces, they encounter various scenes, such as engaging in beer pong or participating in a flirting scenario, wherein they are presented with choices of both alcoholic and nonalcoholic beverages. Adhering to the taxonomy outlined in the Behavior Change Wheel [36], the simulation effectively integrates various behavior change functions, including education, training, modeling, and coercion or incentivization. Notably, individuals within the simulation can interact with role models who demonstrate the refusal to consume alcohol. If the user decides to consume alcohol and accepts an alcoholic drinking choice, the choice results in an incremental increase of a BAC bar,

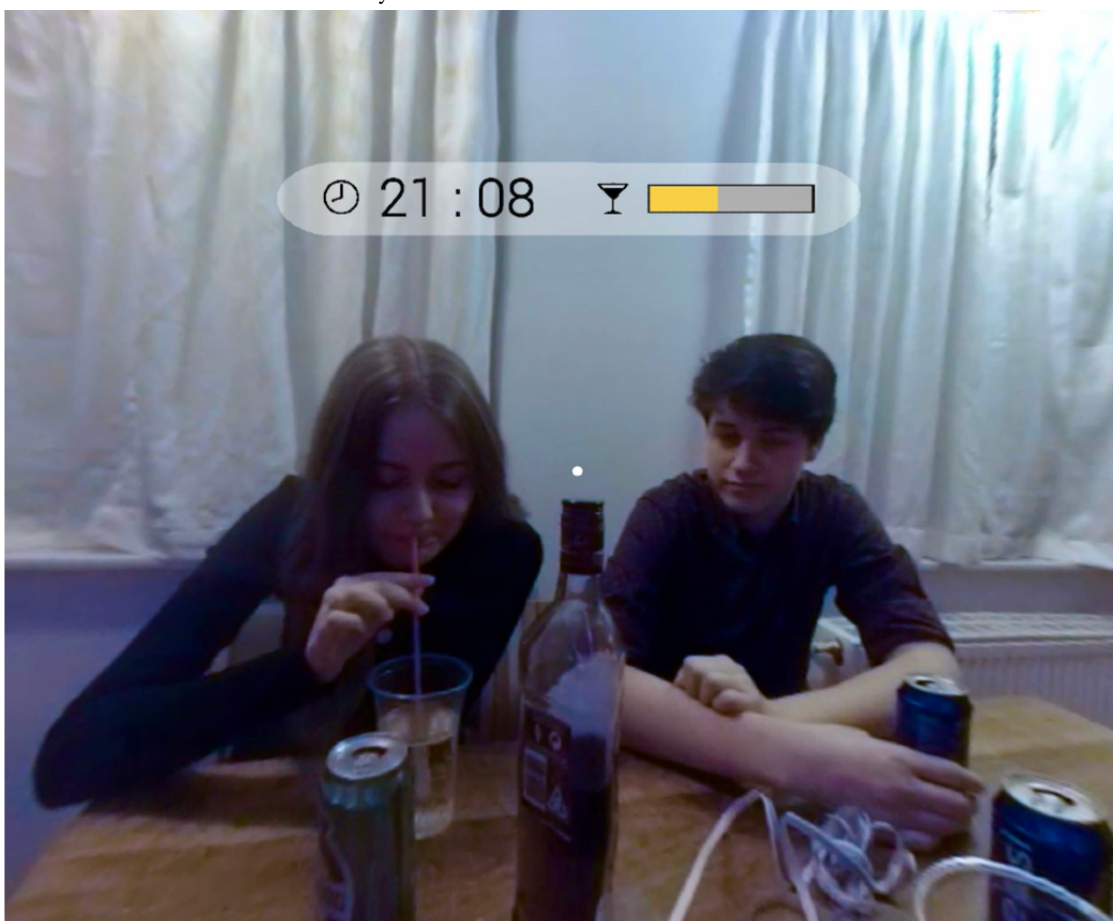
calculated via an algorithm, which is filled in at the top of the screen (see Figure 1, yellow BAC bar at the top of the screen).

This algorithm considers factors like gender, alcohol content in grams, drinking pace, and the average weight of a 16-year-old boy or girl to calculate the BAC [37]. To calculate the exact BAC score, a BAC calculation by Becker and Nielsen [38] was used. The calculation for girls and boys is as follows:



Should the user consume an excessive amount of alcohol within a short span, as determined by the algorithm, they suffer a blackout. This blackout is first portrayed by the camera shaking and a magnifying display of the BAC bar. Following this, within

Figure 1. Screenshot of a scene from the virtual reality simulation FestLab.



Measures

Data were gathered through electronic questionnaires administered during school hours within classroom settings. The questionnaire was developed using the English versions of the respective scales (sensation seeking, drinking refusal skills, refusal communication skills) because no Danish versions were available (Multimedia Appendix 1). For the other measures (alcohol consumption, other drug consumption, knowledge and awareness of BAC) without existing scales in the literature, the project team created their own questions and items. The English questionnaires were translated to Danish and pretested with 31 students to determine their psychometric characteristics.

the game, the screen turns black, with the user subsequently awakening in a bedroom. In this bedroom, they receive messages that they have blacked out, concluding the simulation.

VR FestLab was pre-installed on Oculus Quest (Meta Platforms Inc) VR devices and handed out to the participants. Before engaging with the simulation, adolescents received instructions on device operation and navigation within the simulation. Following this, adolescents experienced VR FestLab for a maximum of 15 minutes in a classroom session. Depending on the simulation decisions, several rounds could be played during this time. After that, a structured 45-minute group reflection period was moderated by a trained study assistant in the classroom.

Adolescents were tasked with completing the questionnaire before (T0) and after (T1) the intervention. Independent variables, including age, gender, alcohol consumption, other drug consumption, sensation seeking, drinking refusal skills, knowledge and awareness of BAC, and refusal communication skills, were assessed at T0 before the VR FestLab intervention. The dependent variable, virtual risk behavior, was surveyed at T1 following the intervention.

Virtual Risk Decisions

The primary outcome was virtual risk decisions, evaluated through a self-developed question: "Did you pass out at any time during the party?" Answer options were dichotomized (yes/no). Passing out can only be achieved in the simulation

when the number and types of drinks accepted in a given time period resulted in a BAC of 2.0 permille, thus representing several risk decisions. The scenes and participant selections within the simulation were intentionally not recorded nor tracked to afford participants the utmost freedom in their interactions. As a result, the blackout experience in the game could only be assessed verbally. If participants responded affirmatively, it was inferred that the simulation terminated prematurely due to excessive alcohol consumption in a condensed time frame during the simulation.

Age and Gender

Participant gender was dichotomously determined using the question “Are you a girl or a boy? (State what you most identify as right now),” while age was quantified using the question “How old are you?”

Perceived Family Affluence, School Performance, and Health

To gather information on the sociodemographic factors of the participants, the following questions were adapted from the Health Behavior in School-aged Children study [39]: “How well-off do you think your family is?” “What does your class teacher(s) think about your school performance compared to your classmates?” and “Would you say your health is...?”

Alcohol Consumption

Alcohol consumption was estimated with 3 single questions designed by the researchers. The questions “Have you ever drunk alcohol?” “Have you ever been drunk?” and “Have you ever had 5 or more drinks on a single occasion?” could be answered dichotomously (yes/no) by the participants.

Other Drug Consumption

To assess the consumption of substances other than alcohol, 5 customized questions were used. Participants were queried about their usage of cigarettes, hookah, e-cigarettes, snuff, or cannabis. Response options were dichotomized (yes/no).

Sensation Seeking

Sensation seeking was measured using the 8-item Brief Sensation Seeking Scale (BSSS-8) by Hoyle et al [40], which has a Cronbach α of 0.76. Participants answered 8 statements using a 5-point Likert scale, ranging from “strongly disagree” to “strongly agree.” The 8-item scale contains 4 subscales with 2 items each. Subscales, including “thrill and adventure seeking,” “experience seeking,” “disinhibition,” and “boredom susceptibility,” were calculated following the criteria outlined by Hoyle et al [40]. The Cronbach α of the BSSS-8 was 0.76 in our sample.

Drinking Refusal Skills—Social Pressure Subscale

To evaluate drinking refusal skills within the context of peer pressure, the 5-item social pressure subscale of the Drinking Refusal Self-Efficacy Questionnaire (DRSEQ) by Young et al [41], with a Cronbach α of 0.87, was used. Participants responded on a 6-point Likert scale, ranging from “I am very sure I could not resist drinking” to “I am very sure I could resist drinking.” The Cronbach α of the DRSEQ social pressure subscale was 0.88 in our sample.

Knowledge and Awareness of Blood Alcohol Concentration

Knowledge and awareness of BAC was measured using 2 self-constructed items. Participants were prompted to rate the statements “It is easy for me to estimate my own alcohol tolerance” and “I know how much alcohol I can drink before I get drunk” on a 5-point Likert scale, spanning from “strongly disagree” to “strongly agree.”

Refusal Communication Skills

Refusal communication skills were assessed using 2 items drawn from the Alcohol Misuse Prevention Knowledge Questionnaire by Shope et al [19]. Only 2 items from the questionnaire by Shope et al [19] were used because the other questionnaire items do not cover relevant aspects of VR FestLab [34]. Participants were asked to evaluate the statements “If someone offers me a drink of alcohol and I say no, I can make them take no for an answer” and “If my best friends want me to drink beer with them and I don’t want to, I have ways to say no” on a 5-point Likert scale, ranging from “strongly disagree” to “strongly agree.”

Statistical Analysis

Data analysis was performed using the R Studio software package (version 2022.07.2). The 2-step methodology, as outlined by Herting and Costner [42], was used to calculate model fit as the first step and formulate the structural equation model as the second step. Initially, confirmatory factor analysis (CFA) using the lavaan package [43] was carried out to determine the adequacy of the measurement models of the questionnaires. For this purpose, different single-factor models were created and calculated using a diagonally weighted least squares estimator that is suitable for categorical items. Model fit was checked using a chi-square test in combination with other fit indices such as the comparative fit index ($CFI \geq 0.95$), root mean square error of approximation ($RMSEA \leq 0.06$), Tucker-Lewis index (≥ 0.95), and standardized root mean square residual ($SRMR \leq 0.08$) [44].

Subsequently, a structural model with latent variables was calculated to investigate the influence of the constructs (alcohol consumption, other drug consumption, sensation seeking, drinking refusal skills, knowledge and awareness of BAC, and refusal communication skills) on the main outcome (virtual risk decisions) and the correlation of the constructs with age and gender as covariates. In addition, a moderation analysis for gender and age was run. Estimated scores for each latent variable were calculated and subsequently incorporated into a logistic regression model to predict virtual risk decisions.

Results

Participants

A total of 268 students from 7 schools were assigned to the intervention group. Of these, 183 students participated in the baseline survey (T0). The main reasons for dropout between allocation and baseline survey were that 1 complete school (n=36) dropped out, 1 complete school class (n=15) dropped out, and 34 students were not willing to participate or did not

provide consent. After the intervention, 2 additional participants dropped out, resulting in 181 individuals completing the first follow-up questionnaire (T1). The subsequent analysis was based on a complete data set from 161 participants. Additional information on allocation and dropouts can be found elsewhere [34]. To test whether there were differences between respondents at T1 and those who provided complete information at T1 and were included in the analysis, independent *t* tests were conducted for metric variables, and chi-square tests were conducted for nominal and ordinal scaled sociodemographic variables. The analyses showed no differences between the 2 groups in terms of age ($t_{179}=0.61, P=.54$), gender ($\chi^2_1=0.31, P=.58$), and Family Affluence Scale (FAS; $\chi^2_1=0.25, P=.42$). For the chi-square analysis of the FAS between completers and noncompleters,

the prerequisite of cell frequencies above 5 was violated, which is why a Fisher exact test was used.

Sample Characteristics

Table 1 provides an overview of the demographic attributes. Gender distribution was equal, with 78 of the 161 (48.4%) participants being female. The mean age of the sample was 15.6 (SD 0.72) years. Most respondents (143/161, 88.8%) reported low to moderate perceived family affluence, and 62.1% (100/161) rated their perceived school performance as good to very good. Additionally, 79.5% (128/161) reported good to very good health. The majority of respondents (119/161, 73.9%) reported having engaged in binge drinking at some point in their lives.

Table 1. Characteristics of the study population (n=161).

| Characteristics | Value |
|---|-------------|
| Age (years), mean (SD) | 15.6 (0.72) |
| Gender (female), n (%) | 78 (48.4) |
| Perceived family affluence, n (%) | |
| Low to medium | 143 (88.8) |
| High to very high | 18 (11.2) |
| Perceived school performance, n (%) | |
| Good to very good | 100 (62.1) |
| Below average to average | 61 (37.9) |
| Perceived health and well-being, n (%) | |
| Good to excellent | 128 (79.5) |
| Poor to fair | 33 (20.5) |
| Lifetime binge drinking, n (%) | |
| Yes | 119 (73.9) |
| No | 42 (26.1) |

Calculations of Model Fit

The single-factor models generally showed a good fit in the CFA and could therefore be transferred to the structural equation model without adjustments. Sensation seeking provided a mediocre fit, with CFI and RMSEA beyond their cut-offs, while the 90% CI of the RMSEA included the cut-off (see Table 2). The factors “knowledge and awareness of BAC” and “refusal

communication skills” were combined for the CFA for statistical reasons; otherwise, it would not have been possible to determine the fit, as they only contained 2 items each. Finally, the combination of the 2 factors showed high loadings on the individual and superordinate factors, which resulted in good fit values in the CFA. The results of the single-factor models are shown in Table 2 and Figure 2.

Table 2. The goodness of fit indices of the confirmatory factor analysis for single-factor models.

| Model | Items | χ^2 test (df) | P value | CFI ^a | TLI ^b | SRMR ^c | RMSEA ^d (90% CI) | P value |
|--|-------|--------------------|---------|------------------|------------------|-------------------|-----------------------------|---------|
| Alcohol consumption | 3 | 2.24 (2) | .33 | 1.00 | 1.00 | 0.04 | 0.03 (0.00-0.16) | .46 |
| Other drug consumption | 5 | 3.02 (5) | .70 | 1.00 | 1.00 | 0.02 | 0.00 (0.00-0.08) | .84 |
| Sensation seeking | 4 | 7.38 (2) | .03 | 0.92 | 0.76 | 0.05 | 0.13 (0.04-0.23) | .07 |
| Drinking refusal skills: social pressure subscale | 5 | 19.47 (5) | .01 | 0.97 | 0.95 | 0.03 | 0.13 (0.08-0.20) | .01 |
| Knowledge of BAC ^e and refusal communication skills | 4 | 1.42 (1) | .23 | 1.00 | 0.99 | 0.02 | 0.05 (0.00-0.22) | .32 |

^aCFI: comparative fit index.

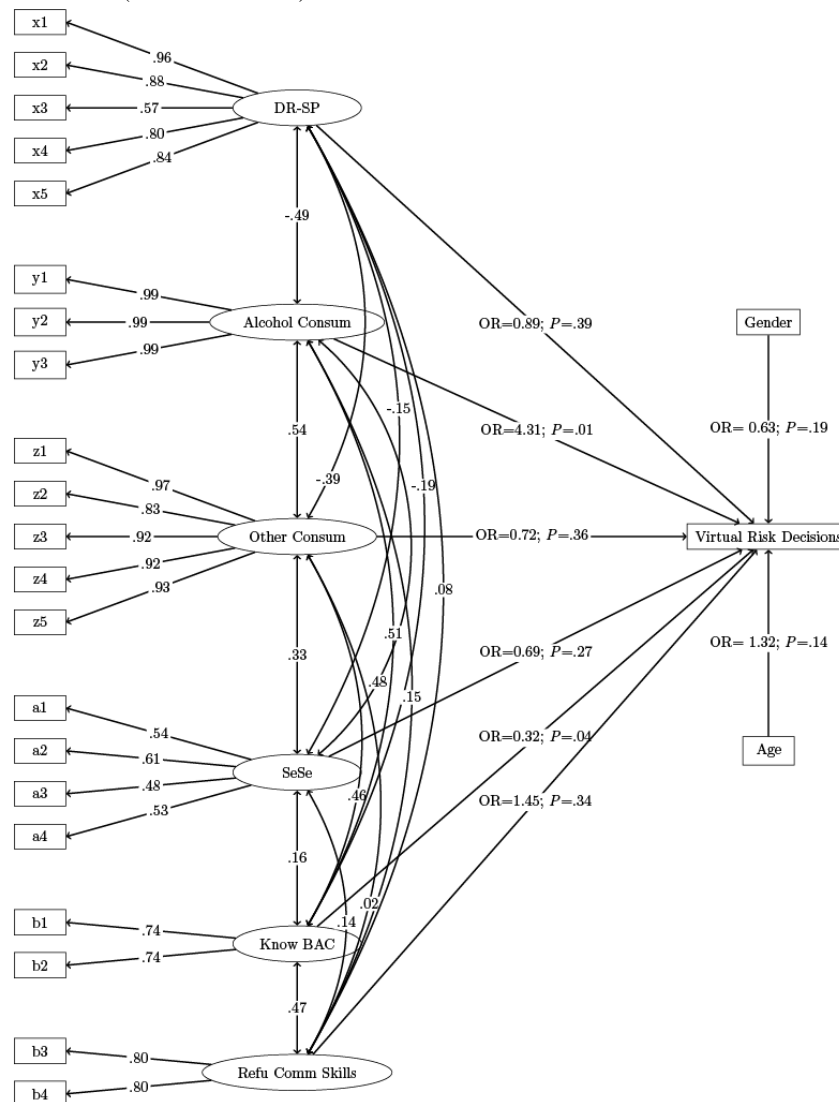
^bTLI: Tucker-Lewis index.

^cSRMR: standardized root mean square residual.

^dRMSEA: root mean square error of approximation.

^eBAC: blood alcohol concentration.

Figure 2. Path model of the relationships between virtual risk decisions and drinking-refusal skills-social pressure (DR-SP), alcohol consumption (Alcohol Consum), other drug consumption (Other Consum), sensation seeking (SeSe), knowledge and awareness of blood alcohol concentration (Know BAC), and refusal communication skills (Refu Comm Skills). OR: odds ratio.



Determinants Linked to Risky Drinking Decisions

A general overview of the bivariate correlations of all variables used in this study can be found in [Multimedia Appendix 2](#). Age and gender were included as covariates without moderation in the structural equation model, as shown in [Figure 2](#). The path model used to test the formulated hypotheses showed an unsatisfying model fit: $\chi^2_{238,161}=422.59$, $P<.001$; CFI=0.94, SRMR=0.12, RMSEA=0.07 (90% CI 0.06-0.08). Nevertheless, we decided to retain the model, because all included measurement models were a priori tested and showed good fit. Due to the explorative nature of the study, the structural model included all possible paths. Therefore, the reason for misfit can be attributed to the cross-loadings of various scales only. As the structural part of the model was the aim of the study, we decided to retain it. [Figure 2](#) shows the tested model. Prior alcohol experiences and knowledge and awareness of BAC were significantly associated with virtual risk decisions in VR FestLab. Participants who reported prior alcohol consumption had a 4.31-fold higher chance of showing virtual risk decisions in the simulation (odds ratio [OR] 4.31, 95% CI 1.70-10.84; $P=.01$). Therefore, hypothesis 3 could be accepted. Apart from that, adolescents with high knowledge and awareness of BAC at baseline were 0.32 times less likely to make virtual risk decisions in the simulation (OR 0.32, 95% CI 0.11-0.93; $P=.04$). Higher social pressure drinking refusal skills (OR 0.89, 95% CI 0.69-1.16; $P=.39$), consumption of other drugs (OR 0.72, 95% CI 0.36-1.45; $P=.36$), sensation seeking (OR 0.69, 95% CI 0.36-1.34; $P=.27$), or refusal communication skills (OR 1.45, 95% CI 0.68-3.10; $P=.34$) showed no significant relationship with virtual risk decisions in the simulation. Therefore, hypotheses 1 had to be rejected, and hypothesis 2 could only be partially confirmed.

Moderation Effects of Gender or Age Regarding Virtual Risk Decisions

Subsequently, we analyzed whether age and gender had a moderating influence on the latent variables. The results of this moderation analysis are presented in [Multimedia Appendix 3](#). All individual moderation analyses for the variables (alcohol consumption, other drug consumption, sensation seeking, drinking refusal skills, knowledge and awareness of BAC, and refusal communication skills) showed no significant moderation. Accordingly, age and gender did not significantly alter the effects of the tested constructs on virtual risk decisions in the simulation. Age and gender also did not significantly influence the dependent variable of virtual risk decisions ([Multimedia Appendix 3](#)).

Discussion

Principal Findings

In summary, the structural equation model exhibited a significant association between prior alcohol experiences and knowledge and awareness of BAC with virtual risk decisions, supporting hypothesis 3. The other initially hypothesized factors (hypotheses 1 and 2), including drinking refusal skills, sensation seeking, refusal communication skills, and consumption of other drugs, did not have significant associations with virtual risk

decisions. Upon exploring moderating factors such as age and gender, no moderation on virtual risk decisions was identified. This study has underscored that prior alcohol experiences are notably linked to virtual risk decisions. Participants who have encountered alcohol and engaged in binge drinking appear to perceive the VR FestLab game as realistically simulating their personal behaviors, leading them to enact these behaviors within the game. Apart from that, it appears that higher knowledge and awareness of BAC is a protective factor and leads to fewer virtual risk decisions in the simulation.

Comparison With Prior Work

These findings align with qualitative insights collected from focus group investigations involving adolescents discussing the simulation [45,46]. Adolescents reported finding the VR simulation remarkably realistic, evoking sensations akin to being present at an actual party [45,46]. The initial participation in VR FestLab possibly aimed to ascertain whether the simulated party aligned with their expectations and whether outcomes matched real-world drinking behaviors. The study's data set does not offer insights into potential variations in behavior between several attempts with VR FestLab. However, it seems plausible that distinct behaviors and strategies would be attempted in subsequent trials, as highlighted by focus group participants in qualitative interviews. The participants expressed the view that VR serves as a medium for experimenting with various behaviors and that repeated engagements with the VR simulation allow for exploring different strategies, such as drinking versus abstaining, while observing the reactions of simulation characters [46]. This points to VR's potential benefit in alcohol prevention, allowing participants to experiment with diverse approaches and behaviors in risky scenarios. This study found a relatively high lifetime prevalence of binge drinking in the group of adolescents aged 14 years to 18 years, at about 73.9% (119/161). In this context, it would be interesting for future studies to investigate the association between previous alcohol consumption and the likelihood of risk decisions in different social environments. These results may also provide hints for further virtual scenarios that can be integrated into the VR FestLab. Hadley et al [47], who combined VR environments with emotion regulation and a risk reduction intervention, also arrived at similar conclusions, indicating that VR, through better simulated contextual cues of risky situations, facilitates the application of different emotion regulation strategies among adolescents. In the real world, such experimentation of behavioral strategies is constrained by the necessity of personally experiencing risky behavior and its consequences, often without the possibility of multiple trials (eg, in the case of blackout).

The hypothesis that individuals with high sensation-seeking tendencies would exhibit elevated virtual risk decisions within the game could not be substantiated by the study's findings. The lack of a significant association between sensation seeking and virtual risk decisions could potentially be attributed to the design of VR FestLab. The game's preventive nature might not have resonated sufficiently with individuals displaying high sensation-seeking behavior. Given that sensation seeking characterizes those seeking diverse, potentially risky experiences [48], the simulated risk behavior in VR FestLab might not have

provided compelling cues for such participants. Participants were aware of the virtual and simulated nature of the risk decisions, possibly leading to the observed absence of virtual risk decisions in the game. This absence could also stem from the absence of personal consequences, such as intoxication, emotional arousal, and sensory perceptions, conveyed through VR FestLab. This lack of stimuli might not engage adolescents with a high sensation-seeking drive. On the contrary, sensation seeking is a multifaceted construct, not exclusively tied to risky behavior. The study by Ravert and Donnellan [49] found that sensation seeking, manifested as a search for stimulation, could also be positively linked to psychological well-being. Furthermore, sensation seeking might have been manifest in nonalcohol-related scenes within VR FestLab (eg, interactions with game characters), rendering the presumed virtual risk decisions unappealing to participants with pronounced sensation-seeking tendencies.

Likewise, drinking refusal self-efficacy skills failed to display an association with reduced virtual risk decisions in this study. Those with higher baseline drinking refusal self-efficacy skills might have opted for less risky drinking decisions within VR FestLab, possibly bypassing activities like beer pong. These observations align with those of the study by Guldager et al [34] that assessed the efficacy of VR FestLab. Although effects were insignificant, a more pronounced increase in drinking refusal skills was noted among participants whose baseline skills lay below the median compared with those above the median. Despite the documented real-world associations between risky behavior and higher drinking refusal skills, drug consumption, and refusal communication skills [50,51], these correlations did not manifest in the virtual world.

Although it was originally hypothesized that higher refusal communication skills would be associated with a reduction in virtual risk decisions, this hypothesis was not supported by this study. It is possible that participants were more exploratory when playing VR FestLab to “just see what happens next” and did not use their refusal communication skills in the simulation to say no to drinking offers. Qualitative interviews with adolescents who played VR FestLab revealed that they felt the peer pressure in the simulation was weaker than in real life [45], which could be a reason why refusal communication skills were not associated with reduced virtual risk decisions in this study.

Apart from that, this study has shown that individuals with higher knowledge and awareness of BAC are less likely to make risky decisions in virtual environments. It is reasonable to assume that those who understand how different drinks affect BAC are less likely to engage in risky decisions in VR FestLab compared with those who cannot accurately assess the effects of BAC. These assumptions are supported by the literature, which indicates that individuals with greater knowledge of low-risk alcohol consumption are more likely to reduce their alcohol intake and make fewer risky decisions [52]. Increased awareness of BAC could enhance risk perception and enable better anticipation and assessment of the consequences of risk decisions. It is possible that individuals without knowledge and awareness of BAC were more willing to experiment in the simulation, leading to an increase in virtual risk-taking decisions. VR FestLab is a prevention program that uses an in-game BAC

bar to illustrate the effects of alcohol-related decisions on BAC. The in-game presentation may help adolescents avoid risky decisions by increasing their knowledge of BAC. Other research [53] using VR in e-cigarette prevention has also shown that virtual prevention simulations can increase substance-related knowledge and harmful perceptions about e-cigarettes.

To our knowledge, this study is the first attempt to examine the relationship between real-life behavior and attitudes and virtual risk decisions in the context of alcohol prevention, making it difficult to contextualize the findings with those of other virtual alcohol prevention studies. The findings illuminate VR's capacity to replicate real-life behavior within simulated environments. Other studies [54-56] using VR in other thematic areas have also concluded that there are links between simulated behavior and real behavior. The combination of prevention and VR within research is relatively novel, necessitating further exploration into leveraging simulated settings for risk behavior prevention and health promotion. Existing studies underscore increasing adoption of VR for prevention and health promotion [57]. Building behavior change interventions and predicting behavioral transformations are challenging in real-world scenarios [58]. Immersive technologies, such as VR, can harness specific attributes like training and realism to facilitate future behavioral change. Nevertheless, the translation of real-life behavior into virtual simulations, along with the potential impact of virtually acquired behavioral patterns on subsequent real-world behavior, remains uncertain. Research suggests that altering an individual's avatar representation in VR influences their behavior and psychological disposition in the real world, an occurrence termed the Proteus effect [24,59]. This phenomenon could also be probed in the context of alcohol prevention, where avatars could shape participants' self-image and preventive behaviors. Addressing these unresolved questions in future studies while delving into the mechanisms at play in virtual simulations could position VR as a valuable asset in prevention and health promotion.

Limitations

In this study, certain limitations must be acknowledged when interpreting the results. First, the applicability of the findings warrants consideration. Participants were drawn from diverse Danish schools, making the results pertinent exclusively to Danish students. Additionally, the recruitment was limited to a specific region within Denmark, implying that adolescents from other regions within Denmark or other countries might exhibit disparate outcomes.

Second, the results should be cautiously approached due to the reliance on self-reported data, which are susceptible to common biases such as respondent bias, extreme responding, and social desirability bias [60]. These potential biases could have influenced and skewed the reported results. The timing of the follow-up data collection (T1), conducted immediately after the intervention, may have influenced the results. Furthermore, this study did not survey risk behaviors that may occur prior to a blackout, such as engaging in sexual activity or driving under the influence of alcohol. Future studies should consider measuring these risk behaviors before a blackout occurs in order to establish a relationship. Specifically, the question about

certain risk decisions may have been biased (eg, experiencing a blackout). The potential for a Hawthorne effect should be considered when interpreting the results, because the students in the intervention group were not blinded and tested the new VR FestLab application. Their knowledge of participation in the study and the aim of VR FestLab can influence their self-assessment of whether they experienced a blackout in the application, which could potentially distort the results. Since there was no content tracking during participants' engagement with the simulation, the navigation patterns within the simulation remain uncharted. Integrating a content log in future analyses could offer deeper insights into participants' usage behavior.

Third, organizational limitations limited the playing time to 15 minutes for each participant. This restriction could have led to variations in the number of rounds played within the simulation, potentially affecting the reported outcomes. Additionally, the controlled setting of the VR FestLab intervention study might have curtailed the expression of extreme behaviors that could

naturally occur among adolescents. This controlled environment may have influenced the observed results.

Conclusions

Despite these limitations, this study illuminates the link between real-life behavior and virtual simulations in alcohol prevention. The significance of prior alcohol experiences in shaping virtual risk decisions underscores the potential of VR to mimic real behaviors. The study highlights VR's potential as a valuable tool for behavior change interventions and health promotion. To harness this potential, future research should delve into mechanisms underpinning behavioral expression in virtual environments. As VR evolves, it presents a promising avenue for health promotion strategies, offering a unique medium to experiment with behaviors in risk-prone scenarios. This research signifies the importance of advancing our understanding of the intersection between human behavior, virtual simulations, and their real-world implications.

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Data Availability

The analyzed data can be accessed from the Zenodo database [61].

Authors' Contributions

CS acquired the funding, provided project administration, and supervised the study. RH, CS, and JDG conceptualized the study, curated the data, and performed the formal analysis. RH, DS, and CS created the visualizations and designed the methodology. JDG, PBL, GM, and CS performed the investigation, and CS, PBL, and GM secured the resources. PBL and GM provided the software. RH, JDG, DS, and CS performed the validation and wrote the original draft of the manuscript. All authors reviewed and edited the manuscript draft.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Investigator-developed questionnaire.

[PDF File (Adobe PDF File), 290 KB - [xr_v1i1e56188_app1.pdf](#)]

Multimedia Appendix 2

Bivariate correlations of all variables.

[PDF File (Adobe PDF File), 212 KB - [xr_v1i1e56188_app2.pdf](#)]

Multimedia Appendix 3

Results of the moderation analyses.

[PDF File (Adobe PDF File), 135 KB - [xr_v1i1e56188_app3.pdf](#)]

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Abbreviations

- BAC:** blood alcohol concentration
- BSSS:** Brief Sensation Seeking Scale
- CFA:** confirmatory factor analysis
- CFI:** comparative fit index
- DRSEQ:** Drinking Refusal Self-Efficacy Questionnaire
- FAS:** Family Affluence Scale
- OR:** odds ratio
- RMSEA:** root mean square error of approximation
- SRMR:** standardized root mean square residual
- TLI:** Tucker-Lewis index
- VR:** virtual reality

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Original Paper

Exploring How Virtual Reality Could Be Used to Treat Eating Disorders: Qualitative Study of People With Eating Disorders and Clinicians Who Treat Them

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Abstract

Background: Immersive virtual reality (VR) interventions are being developed and trialed for use in the treatment of eating disorders. However, little work has explored the opinions of people with eating disorders, or the clinicians who treat them, on the possible use of VR in this context.

Objective: This study aims to use qualitative methodology to explore the views of people with eating disorders, and clinicians who treat them, on the possible use of VR in the treatment of eating disorders.

Methods: We conducted a series of focus groups and interviews with people with lived experience of eating disorders and clinicians on their views about VR and how it could potentially be used in the treatment of eating disorders. People with lived experience of eating disorders were recruited between October and December 2020, with focus groups held online between November 2020 and February 2021; clinicians were recruited in September 2021 and interviewed between September and October 2021. We took a thematic approach to analyzing the resulting qualitative data.

Results: We conducted 3 focus groups with 10 individuals with a current or previous eating disorder, 2 focus groups with 4 participants, and 1 with 2 participants. We held individual interviews with 4 clinicians experienced in treating people with eating disorders. Clinicians were all interviewed one-to-one because of difficulties in scheduling mutually convenient groups. We describe themes around representing the body in VR, potential therapeutic uses for VR, the strengths and limitations of VR in this context, and the practicalities of delivering VR therapy. Suggested therapeutic uses were to practice challenging situations around food-related and weight/appearance-related scenarios and interactions, to retrain attention, the representation of the body, to represent the eating disorder, for psychoeducation, and to enable therapeutic conversations with oneself. There was a substantial agreement between the groups on these themes.

Conclusions: People with lived experience of eating disorders and clinicians with experience in treating eating disorders generated many ideas as to how VR could be used as a part of eating disorders treatment. They were also aware of potential limitations and expressed the need for caution around how bodies are represented in a VR setting.

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KEYWORDS

eating disorders; virtual reality; anorexia nervosa; bulimia nervosa; EDNOS; treatment; immersive; clinicians; qualitative data; psychoeducation; therapeutic; limitations

Introduction

Eating disorders are serious mental illnesses, affecting around 8% of women and 2% of men at some point in their lives [1]. They have substantial physical [2,3] and psychiatric [4] comorbidities, with anorexia nervosa having the highest mortality of any psychiatric illness [5]. Nationally representative population data from England show that rates of possible eating disorders in adolescents almost doubled from 6.7% in 2017 to 13.0% in 2021 [6]. Meanwhile, at 10-year follow-ups, only one-third of those with anorexia nervosa and two-thirds of those with bulimia nervosa have fully recovered [7], and rates of relapse are up to 50% in those with anorexia nervosa [8]. New treatments are thus urgently needed.

Virtual reality (VR), a technology which “immerses users in a fully digital environment through a headset or surrounding display” (p. 3) [9] is a candidate modality for such novel treatments. VR shows promise in treating mental illnesses, with studies demonstrating efficacy in treating phobias, including fear of heights [10] and spiders [11]; anxiety disorders [12]; and avoidance and distress in people with psychosis [13]. Emerging evidence suggests that VR can be useful in the treatment of eating disorders, with a meta-analysis showing reductions in binge frequency and body dissatisfaction in binge-purge and binge-eating disorders [14]. Some evidence also suggests that exposure to a larger version of one’s own body in VR may be a useful addition to the treatment of anorexia nervosa [15,16].

One problem with the currently established treatments for eating disorders is the high rate of dropouts. Even in randomized controlled trials, as many as 40% of participants do not complete treatment for anorexia nervosa [17]. For new treatments to have the best chance of being acceptable to patients, a prerequisite for efficacy, they should be designed in collaboration with the patient group for whom they are intended. To our knowledge, no previous work has explored the perspectives of people with lived experience of eating disorders on the potential use of VR in their treatment.

There is also a longstanding acknowledgment of the difficulty in ensuring that patients receive evidence-based treatments, variously termed an “evidence to practice gap” [18], “implementation problem” [19], or “second translational gap” [20]. This is a particular challenge for complex interventions. To avoid or shorten this gap, it is argued that new interventions should be designed with implementation in mind and that frontline clinicians should also be involved in novel intervention design from the outset. In relation to the growing field of

developing clinical interventions using VR, an international working group of Virtual Reality Clinical Outcomes Research Experts also state that “it is vital to include the patients’ voice early and often in the development of VR treatments” (p. 2), as well as seeking input from health care providers, to design acceptable, feasible, and effective VR treatments [21].

We therefore set out to conduct a series of focus groups and one-to-one interviews with both people with lived experience of eating disorders and, separately, the clinicians who treat them. We explored their thoughts about using a VR environment, including their ideas about the potential therapeutic uses of VR, and any concerns or worries about risks.

Methods

Participants

We recruited participants with lived experience of eating disorders via social media, through the UK eating disorders charity the Somerset and Wessex Eating Disorder Association, and by contacting those on a list of research-interested individuals with eating disorders held by HB. We recruited clinicians with experience in treating people with eating disorders via social media and by snowballing via professional contacts. Potentially interested participants completed a brief online screening questionnaire via SurveyMonkey (SurveyMonkey Inc.; [Multimedia Appendices 1 and 2](#)) to check they met inclusion criteria.

Inclusion criteria for people with lived experience of an eating disorder required that they be aged 16 or over, and have any current or previous eating disorder (eg, anorexia nervosa, bulimia nervosa, binge eating disorder, or other specified feeding or eating disorder). We did not specify that participants must be based in the United Kingdom. We excluded people currently being treated as an inpatient in a hospital. Inclusion criteria for clinicians required that they be a health professional with at least six months’ experience in treating people with eating disorders. Inclusion criteria for both groups required fluency in English (due to a lack of funding for translators) and the ability to access a private space with an internet-enabled device via which they could join an online focus group or interview. We did not require participants to have any previous experience of using VR. We conducted interviews and focus groups online as a result of constraints around in-person research during the COVID-19 pandemic. All participants provided written consent and were offered a £10 (US \$12.5) shopping voucher to thank them for their time.

After recruiting the first 8 eligible participants who were women and who responded to follow-up emails, we excluded subsequent

responders who were women to include men. All eligible clinicians who responded to follow-up emails were included.

People with lived experience of eating disorders were recruited between October and December 2020, and focus groups were held online between November 2020 and February 2021; clinicians were recruited in September 2021 and interviewed between September and October 2021.

Ethics Approval

The study was approved by the Faculty of Health Science Research Ethics Committee, University of Bristol (reference number 7545).

Procedure

We collected brief demographic data, including age, gender (participants were asked “How would you describe your gender?”) and ethnicity, duration of current or previous eating disorder (for people with lived experience of eating disorders), professional background (for clinicians), and duration of experience in treating people with eating disorders (clinicians).

Interview and focus group discussion topics were informed by a topic guide (available in [Multimedia Appendices 3 and 4](#)). We also shared some slides with images of VR headsets and from some VR games and current VR interventions for those with fear of heights and psychosis (see [Multimedia Appendix 5](#)). We used open-ended questioning and follow-up probes to explore participants’ ideas in detail and also allowed them to suggest and discuss issues of importance that were not included in the topic guide. All interviews and focus groups were then conducted via videoconferencing software (Microsoft Teams; Microsoft Corporation), audio-recorded on an encrypted recording device, and transcribed verbatim. Authors HB and LB ran the focus groups together, enabling one of them to monitor the written “chat” function and provide support to any distressed participant if necessary. HB conducted the one-to-one interviews alone.

Analysis

We used a thematic approach, with MRK, HB, and LB all taking part in coding. These coauthors brought differing perspectives and expertise to the data: LB as an associate professor in qualitative mental health research, MRK as a more junior qualitative researcher in health and ethics, and HB as a child and adolescent psychiatrist with research and clinical expertise in eating disorders. HB’s clinical expertise likely influenced the lines of inquiry taken within the interviews and allowed greater probing of the participants, but may have introduced bias. This clinical perspective is likely to have been

counterbalanced by LB and MRK approaching the interviews and analyses from their complementary and nonclinical perspectives. MRK conducted the initial coding of 2 focus groups. Sections of the data from these 2 focus groups were then coded separately by coauthors LB and HB, with high levels of concordance in the coding. LB, HB, and MRK held a series of meetings to finalize the coding frame, and MRK then applied this frame to the final focus group. As the coding frame evolved, codes were grouped to derive themes and subthemes.

MRK then applied the same coding frame to the clinician interviews. Subsections of these interviews were coded by LB and HB, and further meetings were held between HB, MRK, and LB to finalize agreement on these codes. The coding frame evolved through the addition of new ideas from clinician participants and through discussion, we grouped the codes into themes and subthemes. MRK then wrote a descriptive account of the themes and subthemes to explore in detail their content and relationships.

Results

Participant Characteristics

A total of 14 participants contributed to these data: 10 people with lived experience of eating disorders and 4 clinicians ([Table 1](#)). People with lived experience of eating disorders included both people with a current eating disorder and people who have recovered. The length of illness varied from 3 to 20 years. Clinicians came from a range of professional backgrounds and had between 2 and 15 years’ experience of working with people with lived experience of eating disorders. We recruited men and women in both groups.

The screening survey was completed by 31 respondents with lived experience: 5 did not fully complete the survey or supply contact details, 8 did not respond to email invitations to join a focus group, and 8 were women who responded after we had held 2 focus groups with women and were purposively sampling participants who were men. These 21 respondents were therefore not included, and the remaining 10 joined a focus group. Nine clinicians completed the screening questionnaire: 3 did not complete it fully or supply contact details, and 2 did not respond to email invitations.

We held a total of 3 focus groups for people with lived experience of eating disorders: 2 with 4 participants and 1 with 2 participants. As a result of difficulties in finding mutually convenient times, we were not able to hold clinician focus groups and instead held a series of one-to-one interviews.

Table 1. Participant characteristics.

| Characteristics | Values |
|--|--------|
| People with lived experience of eating disorders (n=10) | |
| Gender | |
| Women, n | 8 |
| Men, n | 2 |
| Age (years), range | 19-37 |
| Ethnicity | |
| White/White British, n | 10 |
| Current eating disorders | |
| Current anorexia nervosa, n | 4 |
| Current bulimia nervosa, n | 2 |
| Duration (years), range | 3-20 |
| Previous eating disorders | |
| Previous anorexia nervosa, n | 5 |
| Previous eating disorder not otherwise specified, n | 1 |
| Duration (years), range | 5-16 |
| Recovered from eating disorders, n | |
| Duration (years), range | 0.25-6 |
| Clinicians (n=4) | |
| Gender | |
| Women, n | 3 |
| Men, n | 1 |
| Age (years) | |
| 25-34, n | 1 |
| 35-44, n | 1 |
| 45-54, n | 1 |
| 55-64, n | 1 |
| Ethnicity | |
| White/White British, n | 4 |
| Duration (years) of clinical experience with people with eating disorders, range | 2-15 |
| Professional background | |
| Clinical psychologist, n | 1 |
| Counselor, n | 1 |
| Family therapist, n | 1 |
| Mental health nurse, n | 1 |

Themes

Overview

We describe the core themes: Representing the Self, Strengths and Limitations of VR, Potential VR Interventions, and Practicalities of Delivering VR Therapy. Quotes from people with lived experience of an eating disorder are followed by PWLE, and the number indicates their group (members of groups 1 and 2 were all women; and members of group 3 were

men); quotes from clinicians are indicated CL. Most participants reported having tried VR as entertainment, and those who had not reported that they were willing to try it.

Representing the Self

Everyone acknowledged that deciding how best to represent the self in a VR setting was challenging (“one of the really tough questions” [PWLE3]); “need[s] to be very carefully...done” [CL4]).

People with lived experience of eating disorders felt comfortable with a first-person perspective: “I quite like the idea of just it being from my perspective, so just seeing your feet and hands” [PWLE1]; “I was imagining that you wouldn’t see yourself...you’d see what you would normally see if you were walking around” [PWLE2]. Clinicians agreed: “if I had an eating disorder, I’d probably prefer not having my body [in the VR setting], just having my hands” [CL1], also suggesting that this would increase a sense of embodiment: “[if] I just see my hands, that feels more real because when I’m me, I can’t see my body, unless I look down my body” [CL1]. Some people with lived experience of eating disorders highlighted the importance of accuracy and realism to enable them to suspend disbelief, including representing correct skin color and gender even if only representing a hand.

Some people with lived experience of eating disorders were concerned about the possibility of their whole body being represented, for example, from a third-person perspective or in a mirror, which they felt may exacerbate self-criticism and create risk: “maybe I’ll see something on VR that I’ve never seen in real life and it makes me worse...you might go, wow, I really do look shit in that outfit or you know nude or whatever” [PWLE2]; “with eating disorders being the beast they are, anything that would maybe feed into that kind of inner critic, or that sort of obsession with our sort of external appearance, it would have to be handled very sensitively...for it not to risk causing more harm than good” [PWLE1]. They were also concerned about how accurate images might be created: “wouldn’t you have to take full body photos of people...which in itself I think could be quite difficult” [PWLE1].

There was some concern that an accurately represented body might be distracting: “you would then become too focussed on what it looked like, and then ignore the job in hand” [PWLE2], but participants in both groups also discussed that this itself could form part of treatment (see the “Potential VR Interventions” section).

People with lived experience of eating disorders discussed alternative suggestions as to how their bodies may be represented, such as a “cartoon”-type avatar [PWLE2] or animal [PWLE1]. While such alternatives might be useful to avoid “getting hung up” [PWLE1] on one’s image, they were largely dismissed as unrealistic or silly, and possibly preventing engagement: “I think seeing me like a kind of panda pinballing around...I just wouldn’t...feel like I could get on board with it” [PWLE1].

Representing the self in an abstract form was also suggested and again felt to have therapeutic potential (see the “Potential VR Interventions” section): “maybe they could be shapes, maybe they could be manifested in different things, like personifications, emotions...I actually think that could be part of the process” [PWLE3].

Despite prompting, clinicians expressed few views on how representation should be achieved, tending to share the belief that “it’s best to go with their [PWLE] visualisation, because then it has more meaning” [CL1]. However, participants in both groups agreed the actual process of creating a representation of self could be challenging if this presented patients with excessive

choice: “I would be distracted by worrying what my virtual [cartoon avatar] self looked like if it was down to me [to make it] or whether it was down to someone else to generate me then I might get offended” [PWLE1]. One clinician suggested this process could be simplified: “so that we didn’t have endless conversations about choice...there’s a bit of me that would go for a menu of what somebody looks like so they could choose a torso or...a torso or legs or a face...or the menu would just be certain kinds of figures” [CL3]. One clinician also raised the point that it may be important to discuss the process of leaving VR to return to one’s own real body: “we’re not going to be that avatar so, how do we then come back out into the real world and reconnect with who we really are, even the bits we don’t like” [CL1].

Strengths of VR

People with lived experience of eating disorders and clinicians were excited about the potential of using VR in treating eating disorders and felt it may be more engaging than other treatments: “I would be more motivated to do that as my homework than my mood diaries or my thought diaries” [PWLE3]; “I’d be really interested in it, definitely like give it a go, I imagine young people would just engage very well in it” [CL4].

Participants described the strength of creating realistic situations, which nevertheless were not actually real and so could provide a safe space to practice: “knowing it’s not real, but also it’s simulating something that is real so it would be a very good first approach to...expose somebody to something scary” [PWLE1]; “a gentle form of exposure work” [CL3]. One clinician [CL1] wondered if this might be particularly valuable for some groups of patients, suggesting that those who are autistic or anxious may find it easier to engage in a “real” activity than a face-to-face conversation.

Participants noted that in some ways VR was “better” than real life because it is a “controlled environment” [PWLE2 and CL3] and having control—specifically the ability to stop—allows users to explore or confront activities they would not feel able to try in the real world: “you can always turn it off...you’re not going to be halfway round a roller coaster having a panic attack” [PWLE2]; “you can take it off any time” [PWLE3].

People with lived experience of eating disorders suggested VR could also help make therapy more closely related to real life, by making it more engaging and action-based “I find sitting on the couch in the room [in therapy] really tough, I think it’s [VR] something physical to do, a practical thing to do” [PWLE3]. They also suggested that VR might enable therapeutic work to feel more directly connected to real life because it could enable “the therapist [to be] there with you as you’re experiencing those things...rather than...have to remember these situations and then feed them back...that’s a challenge to remember what you’ve actually thought and felt at that moment in time and then be able to share it with a therapist when you’ve got that meeting...three days later” [PWLE2]. Another person with lived experience of eating disorders explained “I’m going to benefit from maybe being in a room with my therapist and having a sort of virtual reality...challenge and her sort of...being able to be there, in the moment...I think it would help me feel like we’ve

had a better understanding of what it actually feels like in that moment” [PWLE1].

Clinicians discussed the possibility of using VR alongside existing treatments “whatever that end goal is I think that it requires picking up on tools that you think are going to work for that particular individual and I just see VR as being a tool”, adding “if it was available you might be kind of picking it off the shelf” [CL3]. Relatedly, they mentioned its potential as a scalable resource, enabling more support than might otherwise be possible in overstretched services: “potentially then, we know that people are getting something additional to what they are currently able to access often in services” [CL2].

Limitations of VR

Some people thought VR headsets might be heavy, uncomfortable, or hard to take off quickly. Some without personal experience of VR were worried about feeling claustrophobic or “panicky” [PWLE2], though this was countered by the experience of others.

Practical concerns about being unable to see one’s surroundings and feeling off-balance were also raised, contributing to fears about feeling unsafe and “vulnerable” [PWLE1 and PWLE2] while using VR; it was felt that individuals’ experiences may increase such feelings. Participants also described potentially feeling self-conscious, a common experience when trying VR in other contexts: “I think you feel like a bit of a dick when you try it on” [PWLE3].

Both people with lived experience of eating disorders and clinicians were concerned that clinicians might not feel confident about using VR technology, and one person with lived experience of eating disorders also suggested VR was “not for everyone”: “I wouldn’t naturally be very interested in VR to be honest and I think it’s maybe for people who are younger than me” [PWLE3].

Participants also talked about technical limitations relating to the suitability of VR in treating eating disorders. Concerns included the quality of graphics, and that VR may be limited to visual and sound worlds, which would not be able to capture the physical sensations involved in experiencing and recovering from an eating disorder: “when I went through recovery...it was physically existing in a bigger body...like the physical sensation of inhabiting a bigger body...I’m not sure that VR could address” [PWLE1]; “it’s kind of bingeing and then not eating anything, it’s that sense of hunger, like you can’t replicate that with VR” [PWLE1]; “for me there’s an additionality of thinking about smells or sounds” [CL3].

Some clinicians discussed the idea that VR not being real might be unhelpful because it could facilitate avoidance of real life: “fuelling more the idea that we can be this virtual reality person that’s not ourself, because we don’t like ourself” [CL1], or avoidance of treatment: “I think with an eating disorder there’s always this kind of temptation to step away, isn’t there? And actually there is a real need to just get on in there and do it [the

treatment] right away” [CL2]. However, clinicians also described this viewpoint as in “tension” with a recognition of the idea that VR could be used as an intermediate step or “tool” for people who are not yet ready to try things out in real life: “[VR] feels more accessible and then, they feel more kind of empowered and strengthened taking it forwards in the real situations” [CL2].

People with lived experience of eating disorders raised the concern that the fact that it is not real might make VR easier to dismiss: “I might be inclined to think, well that was just in VR, in real life it would be totally different” [PWLE1]; “I think it must be really difficult to...apply it because you think well that wasn’t real” [PWLE2].

One person with lived experience of eating disorders also raised the idea of VR being a fad and the possibility that it could be an expensive distraction from the need to train more therapists

Potential VR Interventions

Participants made a wide range of suggestions for potential VR interventions to help and treat people with eating disorders. They agreed treatments would need to vary for each individual: “ultimately it has to have meaning to the person you’re working with” [CL1]; “no pun intended, one size definitely won’t fit all” [PWLE1]. However, suggestions could be grouped according to the type of intervention.

Practicing Everyday Challenges

One common type of intervention discussed by participants was the idea of using VR to “sort of put yourself in that [challenging] situation as an in-between step before you end up doing it” [PWLE2]; or “practicing helpful behaviours or responses to situations...having an opportunity to try out responding in a different way...so...it could feel much easier to access that in the real world” [CL2]. Challenges fell into 3 main groups: food-related scenarios, weight/appearance-related scenarios, and challenging interactions. Examples are presented in [Table 2](#).

Both groups discussed how VR could allow people with eating disorders to practice such challenges in a protected way, to decrease anxiety or “desensitise” [PWLE2] oneself, thus providing an in-between step before going into a real situation “there’s a whole lot of...step-based approaches to end up with sitting in a café having a piece of cake...[in VR] you’re taking away a whole layer of somebody being concerned about the public’s reaction to them” [CL3]. VR might fill an important gap between talking about doing something and actually doing it: “it’s kind of that buffer, that bridge to being exposed to those things in a real world” [PWLE1]; “it could probably lend itself quite well to practising going up to someone and saying, you know, can I have this drink or whatever, like it would be a good sort of in between step, because otherwise...there’s lots of talking and planning around it but there’s nothing in between that can, you know, reduce their anxiety” [CL4].

Table 2. Quotes about challenges and potential VR interventions.

| Challenges and specific scenarios | Quotes describing challenges | Quotes relating to the proposed VR intervention |
|--|--|--|
| Food-related scenarios | | |
| Cafés | <ul style="list-style-type: none"> going into Costa or whatever and ordering that hot chocolate...those other challenges that are almost kind of like steps before the eating [PWLE2] having to talk to a waiter or...interact in a normal way whilst your brain is feeling anything but normal [PWLE1] | <ul style="list-style-type: none"> getting used to...where all the cakes are on the counter and not feeling too overwhelmed by that [PWLE2] I will never meet the person who's in this situation as a waiter, therefore I can try saying different stuff and then you can kind of repeat the same situation [PWLE1] |
| Supermarkets | <ul style="list-style-type: none"> I really struggled with going into a supermarket to pick a sandwich off the shelf...I get paralysed with the indecision and the kind of temptation to look at calorie labels and the knowledge I shouldn't be [PWLE1] I would struggle with not impulsively buying loads of food for binge eating [PWLE3] | <ul style="list-style-type: none"> making sure like you go down each aisle...when there's like the chocolate aisle or whatever and physically taking one off the shelf, putting it in your basket...trying not to check the calories or seeing other people's responses, actually no one is shouting at you, oh look at the girl, she's got chocolate in her basket...just to get exposure to those sorts of things [PWLE2] |
| Eating in public | <ul style="list-style-type: none"> eating in front of others...if I'm in work I find that almost impossible because you think everybody's watching you [PWLE2] | <ul style="list-style-type: none"> the idea of eating a real meal but in an environment created by the VR. With other people around and again that idea of are people going to be watching me...experiencing that a few times will desensitise me to go out and do it [PWLE2] |
| Portion sizing | <ul style="list-style-type: none"> I don't have a good sense of how much I should be eating or shouldn't be eating [PWLE1] | <ul style="list-style-type: none"> serve yourself a meal from this thing and then you could then say, okay, the nutrients you're getting from that [PWLE1] you could have a go at dishing yourself up a plate of food...and all of a sudden pull out of the cupboard what somebody might consider to be a normal plate of food and have a conversation [CL3] |
| Weight/appearance-related scenarios | | |
| Being weighed | <ul style="list-style-type: none"> I'm happy to get on my own scales now...whereas when I was anorexic it was terrible [PWLE3] | <ul style="list-style-type: none"> having a conversation about how do you feel...looking at those scales being now in your virtual room [PWLE3] perhaps you have an expectation or desire of what you want the number [on the scales] to be and it's not that, or in one scenario it's more than what you expect it to be and how would you feel about that? [PWLE3] |
| Changing rooms/gyms | <ul style="list-style-type: none"> The environment that I felt was really difficult would be changing rooms...I just feel very self-conscious [PWLE3] | <ul style="list-style-type: none"> what is it like to go into a gym where everybody is extremely muscular and like how do I feel about that? [PWLE3] |
| Public places | <ul style="list-style-type: none"> I couldn't walk on the main roads because I thought I was too ugly...I thought...cars...would crash because I was so like shockingly hideous [PWLE3] | <ul style="list-style-type: none"> you could use VR to kind of emulate that feeling of being in a body and being looked at...the feeling of being observed and how to get through that [PWLE1] |
| Clothes shopping | <ul style="list-style-type: none"> one of the biggest limitations if you go clothes shopping and obviously there's great big mirrors everywhere... [PWLE2] | <ul style="list-style-type: none"> with the eating disorder maybe people can wear certain types of clothes or like baggier clothes and actually even trying on like different styles and realising what you might like or what you might like to experiment...kind of finding your own identity slightly more [PWLE2] |

| Challenges and specific scenarios | Quotes describing challenges | Quotes relating to the proposed VR intervention |
|-----------------------------------|---|---|
| Interactions | | |
| Unhelpful comments | <ul style="list-style-type: none"> I find it really hard to know how to respond...where people are talking about say their own weight or their own eating...or...commenting on my weight or my eating [PWLE1] when they go back to school...what they're going to say [about why they've been away]...we tend not to discharge anyone until they've got a plan around that because that feels so difficult for them [CL4] | <ul style="list-style-type: none"> having your therapist there with you going look, okay, so they've said that that's made me think that what, yeah, how do I work this through [PWLE1] |
| Asking for help | <ul style="list-style-type: none"> for me, asking for help was really, really, hard [PWLE3] | <ul style="list-style-type: none"> if we had a virtual reality scenario where I go and they don't give a great response...I can practise how I'm going to respond to that...it could be about easy steps, like level one, you ask for help and somebody does like whatever...and then other situations where it's more difficult...or more confrontational [PWLE3] |
| Practice skills | — ^a | <ul style="list-style-type: none"> a virtual environment to practise...skills that they have in DBT [dialectical behaviour therapy] would have been great [PWLE3] practice anything in terms of like life skills...I think mostly like communicating within a family...practising for what you want [CL4] |

^aNot available.

Both groups also suggested that VR could be used to try out these situations at different levels of difficulty. For example, other avatars in a VR setting could be used to make challenges easier: “maybe you can have someone in the queue before you ordering that and kind of normalising that” [PWLE2], and situations could also be made increasingly challenging: “graded exposure of challenge...depending on what the fear is, is it talking to other people, is it asking for food, is it having the food in front of you. Like any of those number of things you could recreate in virtual reality” [CL4].

VR could also enable discussion about in-the-moment thoughts and feelings about being in a feared situation, in a way that would be more immediate than talking retrospectively in a therapy session: “going as a VR to a restaurant and then you're talking about, how is it making you feel, the fact the person is eating...might be a useful tool” [CL1]; “you could look at a menu and in the session you can kind of go, okay, what's going through your head and you do it as a CBT [cognitive behavioural therapy] thing” [PWLE1]; “being able to expose yourself to kind of challenging situations like that and being able to talk through what your instant thoughts are and then I guess rationalise them a bit more could be helpful” [PWLE2].

Most people with lived experience of eating disorders and clinicians agreed that this could be useful, though a clinician raised a concern: “is it something that would mean they [patients] could practice it and then [be able to do it] or would [it contribute to feeling that] everything has to be done perfect?” [CL4].

Attention

Several people with lived experience of eating disorders described how their attention was affected by their eating disorder, causing them to fixate when in public on, for example, people with particular body types, or food outlets: “it feels very bizarre to me now but like, I remember walking down the high street and it was like I had a zoom cam in my head, like spot the skinniest person in the street, and then I would focus on them all the time and then compare myself to them” [PWLE1].

They suggested VR could be used to help individuals recognize what they were attending to: “I don't know if you can like eyetrack people over the VR” [PWLE2]; “it would be a really useful tool to kind of just confirm that bias” [PWLE2]. Building on this, they suggested VR might then be used to retrain attention: “actually if they're saying...we've just noticed you're looking at this, how about looking at those” [PWLE2]; “it could be a good way of getting rid of those biases and try to see things in a more kind of healthy and realistic way” [PWLE2].

Representing the Body

Body representation was discussed in terms of whether it could be a therapeutic intervention. The suggestions, why they were felt to be potentially helpful, and supporting quotes are presented in Table 3. The ideas comprised representing the body in an abstract way, having a third-person perspective of one's body, or a third-person perspective of one's body at different weights, and comparing self-generated versions of own body with those generated by the clinician. The area was agreed to be complex, with even the act of choosing how one's body should be

represented giving scope for therapeutic discussion around why someone wanted to be represented in a particular way: “if you allowed somebody to choose say their avatar...to get different conversations about the whys and what fors of choice...how do they think somebody would perceive the avatar and why” [CL3].

Table 3. Quotes relating to how representing the body could be therapeutic.

| Representation of the body and how it might help | Illustrative data |
|--|---|
| Abstract/exploratory representation of body | |
| <ul style="list-style-type: none"> Reduce the importance of shape and size in self-evaluation | <ul style="list-style-type: none"> loosen up some of the fixed ideas about your body...lessen the importance of how you view your body [PWLE3] what I looked like...was so central to maintaining anorexia that if there was something that could have helped me shake that up or reconceptualise that, that would have been great...if you could represent yourself, like maybe that's a physical thing or maybe that's also like I want to be courageous or I want to be strong or...I want to climb a mountain [PWLE3] |
| Third-person perspective of own body | |
| <ul style="list-style-type: none"> Understand the severity of the illness | <ul style="list-style-type: none"> if I could have seen myself from the perspective of another in the past I would have been shocked...about how unwell I looked [PWLE3] I had moments [when unwell with anorexia nervosa] of like stepping out of myself and being, my goodness, I look really unwell, whereas most of the time I thought I was overweight [PWLE3] |
| <ul style="list-style-type: none"> Change attitude to own body and reduce avoidance | <ul style="list-style-type: none"> practice the sorts of more positive self-talk...to override some of those really powerful negative comments that come up...but then...being able to step away from it quite easily when it feels too much...A lot of people go through life and just kind of avoid looking at their image...and actually, it's more helpful to be able to look at yourself...focusing on the things that you do like about your body and challenging your ideas about the bits you don't like [CL2] |
| Third-person perspective of own body at different weights | |
| <ul style="list-style-type: none"> Reduce anxiety about planned weight restoration | <ul style="list-style-type: none"> seeing yourself as a bigger weight as a kind of like exposure therapy so you can kind of get your head around what that might look like. [PWLE1] ...it would be a good thing for them to see...and...explore...what they see and how they feel about that [planned weight increase] [CL4] |
| <ul style="list-style-type: none"> Reduce anxiety around small fluctuations in weight | <ul style="list-style-type: none"> nowadays [in recovery]...I'd find that quite useful actually...it would be interesting to see...this is what you look like with or without like a small weight increment and you can't tell the difference [PWLE1] |
| <ul style="list-style-type: none"> Seeing that other people do not react as feared | <ul style="list-style-type: none"> you could see other people's responses to you at that normal weight and just witness that actually people aren't going, oh my gosh, that's huge, or people aren't responding at all [PWLE2] |
| Compare self-generated with VR-generated image | |
| <ul style="list-style-type: none"> Allow comparisons and discussions | <ul style="list-style-type: none"> you could ask somebody...to come up with their own image about what they look like and then overlay the comparison, if somebody can tolerate that...I think those are...helpful possible conversations to have [CL3] |

Various caveats were expressed. These included the idea that some interventions might not be useful for everyone: “other people might potentially find it triggering” [PWLE3], and that it may be unhelpful to focus too much on appearance “the way we look is just a small part of who we are, and there's probably other things we want things to be doing alongside” [CL2].

Manipulating the weight of the body representation was particularly controversial. Some people with lived experience of eating disorders felt it would not be helpful, that they would not want to experience it, or that it may be counterproductive. There were concerns from both clinicians and people with lived experience of eating disorders that it might lead to increased rumination about body size, or lead to further disordered eating behaviors or weight loss: “it really could have

triggered...restricting behaviours if it really kind of distressed me...kind of almost like an anxiety thing like just the fear of kind of knowing what you look like” [PWLE2]; “[if] you don't like what you see and then you go, wow, I don't want that and then it's going to push you down the other way so it's a bit of a risk” [PWLE1].

Another concern was that images of self at a healthier weight might encourage a focus on specific body parts rather than on the overall appearance of looking “well”: “they might just be focussing on, ‘Oh god, there's no thigh gap’ you know...would they be able to see the glowing skin and the healthy hair..?” [CL2]. Some clinicians also wondered if very unwell patients would be able to make use of it, highlighting that it would need to be used in an appropriate and timely fashion: “for somebody

very much in the grip of anorexia...I can imagine you'd have conversations, 'Well, the computer's wrong'" [CL3]. Another question was how it would be possible to know what one's body would look like at a different weight: "you can't really predict what that would be like just through like a computer algorithm" [PWLE1].

There was general agreement that therapeutic work around body representation would be better done with the support of a therapist: "I would only want to do it with a therapist that I trusted rather than having the option to look at it at home" [PWLE2]. This was partly because people wanted to be supported through the process, and partly because they felt it would be useful for someone else to be in control as repeatedly checking might be unhelpful "like controlling the scales and not going on the scales as often as you might otherwise." [PWLE2].

Clinicians also felt that such an intervention would need to be used at the right time in relation to motivation and recovery: "someone that was coming in in a different mindset and...they really did want to change...then yes, maybe it would work" [CL1], and that if used it should not be a drawn out intervention but "quite time-limited or focused bit of work" [CL2].

Representing the Eating Disorder

One person with lived experience of eating disorders had a previous experience of using an art program in VR as a means of illustrating his eating disorder. In it, he "was trying to simulate what happens when you start eating again after starvation...it was also quite good at communicating to other people as well" [PWLE3]. He explained "I'd lived that in difficult feelings and difficult behaviours and stuff but I hadn't been able to communicate it in words and I think that communicating it visually and using space and colour...was really powerful and therapeutic." Part of what had been helpful was "you have the paintbrush and you are in charge, you have agency...it met some of those core needs about agency" [PWLE3]. Another person with lived experience of eating disorders agreed "this is about creativity and doing something different in the space...I think it would really appeal to me" [PWLE3]. One clinician also suggested VR could be used to help patients separate their eating disorder from their idea of themselves, for example, by creating a representation of the eating disorder in the virtual world: "that classic anorexia externalisation process of having anorexia in the room with you...There might be a place for that as well as the young person" [CL3].

Psychoeducation

People with lived experience of eating disorders described their family members, friends, and clinicians finding it hard to understand what they were experiencing: "so much of the pain in the heart of having an eating disorder is people around you just not understanding" [PWLE1]. They suggested that VR training could help others to understand eating disorders better: "to train therapists or charity volunteers or GPs or family to...get that kind of level of understanding and empathy" [PWLE1]. For example, VR could be used to "show the messages, pinging and pinging with all the influencing thoughts that

we get...the fact that you're focusing on you know skinny people, calorie labels, smells..." [PWLE1].

Clinicians agreed VR could be used to "increase family members' understanding" [CL4] and "help them step into a different position" [CL3]. One clinician suggested VR could be used as part of family-based therapy, to coach parents in skills to support their child so that "the parent can go in more likely to get it right, I guess having had a bit of practice with that beforehand" [CL2]. However, they also wondered what might be lost through the young person not witnessing their parent being coached as would be her normal practice "when the young person sees the parent being coached...sometimes that's really helpful because they know...it's not just coming from the parent...it's the professionals."

One person with lived experience of eating disorders suggested that VR could be used to make learning about eating disorders more engaging for those with the illness too: "I think it would be a really good learning module...actually I find concentrating very difficult so to make learning fun and engaging and dynamic" [PWLE3].

Enabling Therapeutic Conversations With Oneself

People with lived experience of eating disorders raised the possibility of VR enabling them to see themselves from an external perspective which will allow them to support themselves better. It could be a "learning opportunity for you to impart some wisdom so could you kind of visualise, like create yourself, you know, is it that kind of shit that they say...would you say this to other people, what you're saying to yourself" [PWLE3].

Practicalities of Delivering VR Therapy

Overview of Opinions

Participants highlighted practical considerations around the delivery of VR therapy, which would vary according to the precise nature of the intervention. Supportive data for this section are available as [Multimedia Appendix 6](#).

Setting

Opinion was divided as to whether people would rather use VR interventions at home or in the clinic. Arguments in favor of the home environment centered around it being less stressful, especially because one would not need to worry about being observed. However, others preferred the idea of a clinic setting because they felt that a potentially difficult or distressing VR experience could intrude on the safety associated with home, and some questioned whether they would use VR if left to do so independently.

Therapist Presence

Many participants in both groups would want therapist involvement in or alongside any VR, with people with lived experience of eating disorders highlighting that they would need to know and trust their clinician. Others suggested that the therapist's input could be intermittent, with VR providing additional support, for example, between or alongside other therapeutic work.

Timing

The best timing for a VR intervention was agreed to be important, complex, and dependent on the nature of the intervention. Some felt that people with eating disorders may not be able to make use of it if they were significantly underweight or not eating, while others suggested it might be useful for people who were very underweight as it might help to manage high levels of anxiety in relation to beginning treatment. Others felt that VR interventions could be useful at any point, and highlighted that the severity of eating disorder symptoms is not always related to weight. Several participants in both groups raised the patient's current motivation for recovery as important, feeling that this might be the most important factor in whether people would engage with and potentially benefit from VR-based treatments.

Discussion

Principal Findings

Both people with lived experience of eating disorders and clinicians with experience in treating eating disorders were in general positive about the possible future use of VR in eating disorders treatment. They generated a wide range of ideas as to how VR could be used, including to practice challenging situations, retrain attention, represent the eating disorder, for psychoeducation, and to enable therapeutic conversations with oneself. They discussed the complexity of how to represent people's bodies in a VR setting and ways in which this could be done safely and potentially therapeutically. Clinicians and people with lived experience of eating disorders independently suggested similar uses for VR, and the coding framework initially developed for the focus groups with people with lived experience of eating disorders fitted well with data obtained from clinicians.

To our knowledge, this is the first study to explore the views of people with lived experience of eating disorders and clinicians about how VR could be used in the treatment of eating disorders. The focus groups and interviews were extremely rich in detail and explored many ideas in substantial depth. Focus groups included people with several different eating disorder diagnoses, including some with experience of more than 1 diagnosis, and both men and women. We also interviewed clinicians (1 man and 3 women) from a range of professional backgrounds and with varying amounts of professional experience.

Participants highlighted some concerns about the limitations of what is possible in VR, particularly around physical sensations and the sense of smell. In fact, haptics can enable participants to experience physical sensations in a VR setting [9], and it is possible to add an olfactory display to VR to allow the user to manipulate objects in VR and have an experience of smelling them [22].

Strengths and Limitations

Although the study was small scale, we adopted a rigorous approach to data collection and analysis. Credibility was enhanced by the inclusion of 2 sample groups recruited nationally and using multiple sampling strategies to maximize variety in the perspectives obtained. Purposive sampling was

used to ensure that perspectives from men were also included, thus increasing the transferability of the findings. Data analysis was carried out with triangulation between 3 researchers, each with differing backgrounds, and 1 of whom was not involved in data collection. To ensure dependability, the researchers performed independent coding and checking across both sample groups and discussed discrepancies in interpretation to arrive at a comprehensive coding schema that could be applied consistently to the data.

However, we identify the following limitations in the study. First, transferability is limited in relation to ethnicity because both our people with lived experience of eating disorders and clinician samples were limited to people who described their ethnicity as White. This was due to difficulties in recruiting people from other ethnic groups in the time available. It would be useful to expand this work to people from different ethnic groups, and with different cultural backgrounds, in the future, to open up conversations around different cultural experiences of eating disorders and VR. Second, the number of clinicians included was small, again as a result of time limitations. Their input was valuable and is novel in this type of work but it would be useful for future studies to include more clinicians. Third, it is likely that the self-selection among individuals offering to participate may have led to us recruiting participants who were more likely to be positive and enthusiastic about the potential adoption of VR. Lastly, it is possible that findings would have been different had we held interviews instead of focus groups with people with lived experience of eating disorders, and focus groups instead of interviews with clinicians. It is possible that this variation in methodologies meant we collected slightly different data from the 2 sample groups because of the format available to them in which to respond. For example, clinicians' views may have been shaped if they had had the opportunity to interact and reflect with colleagues in situ, and people with lived experience of eating disorders may have been less able to draw on personal narratives in a group setting. Ideally, further research could triangulate these 2 methods of data collection using a mix of the 2 approaches in both sample groups. However, it is notable that the focus groups were small, and we observed individual participants talking in-depth, and also that there was a strong overlap and consistency in the content of themes obtained from the 2 sample groups.

Comparison With Prior Work

Previous work has described a case report of a person with lived experience of eating disorders in the context of her trying VR exposure therapy in which she ate "forbidden" foods [23]. The participant described that she initially perceived the foods as too unhealthy to eat even in a virtual setting, and that she was then able to use the VR environment to practice eating feared foods [23]. However, we have been unable to find previous research which has reported qualitative research findings alongside other results in preliminary trials of VR interventions for eating disorders. We have also been unable to find other qualitative studies exploring the views of people with lived experience of eating disorders around how VR could potentially be used in treating eating disorders, despite the importance of this for ensuring that new interventions are acceptable and

therefore have the potential to be effective in treating eating disorders.

There is also little research on the views of health care professionals on the potential use of VR in treating eating disorders. One survey of practicing cognitive behavioral therapists found that 45% agreed VR could be used for eating disorders (rising to 61% among those with clinical experience of treating people with eating disorders) [24]. They agreed with statements around VR enabling exposure to be tailored to the individual, increasing a sense of control, and making exposure less stressful, and shared concerns we found in our study about whether results would translate into the real world and the ability to use a new technology [24].

Early qualitative work in other areas of VR development for health-related use has found some similar general themes, particularly around the idea of VR as being novel and enjoyable [25,26]. When health care professionals are asked about potential applications for VR, they have many ideas [26].

Some qualitative work has explored the experience of people with other mental health conditions while undergoing VR interventions. These report several themes in common with our findings, such as the VR environment feeling “easier than the real thing” (p. 9) [27] or a good place to practice situations “so you cannot make a fool of yourself” (p. 4) [27]. Relatedly, they describe the potential usefulness of VR in reducing anxiety [28] and building confidence [27,28]. Caveats are also consistent, particularly the concern that it might not be for everyone, and

that benefits might not translate out of a VR environment [27]. Participants were also keen to highlight that the use of VR would need to be supported by someone with whom the patient had a trusting relationship [28].

Implications for Research and Practice

Both people with lived experience of eating disorders and clinicians in our study expressed interest and enthusiasm in the development of interventions using VR to supplement and improve the treatment of eating disorders. This work has highlighted a number of possible interventions that could be developed using VR, including psychoeducation, experiencing challenging situations, attention retraining, and seeking to make therapeutic use of the different ways VR enables one to experience one’s own body. We recommend that such interventions are co-designed with people with personal experience of eating disorders, to maximize their usefulness for this group and reduce the risk of unintended harms. Such novel interventions will subsequently require rigorous evaluation in the form of clinical trials to test their efficacy.

Conclusions

People with personal experience of eating disorders and clinicians who are experienced in their treatment both see many potential roles for VR-based interventions in their treatment, although they are also clear that there is a need for caution and ongoing co-design in their development, particularly around how bodies are represented in a VR setting.

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Data Availability

Data are available to bona fide researchers on request via the University of Bristol Research Data Storage Facility (deposit doi: 10.5523/bris.lpf0ek7zcnxb26yzhe8a5khhbx).

Authors' Contributions

HB, IPV, LB, and LMT researched the literature and conceived the study. HB, IPV, LB, JB, and LMT were involved in protocol development and gaining ethics approval. HB recruited participants. HB and LB collected the data. MRK, HB, and LB were involved in data analysis. HB wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Screening questions for people with lived experience of eating disorders.

[[DOCX File, 22 KB - xr_v1i1e47382_app1.docx](#)]

Multimedia Appendix 2

Screening questions for clinicians.

[[DOCX File, 22 KB - xr_v1i1e47382_app2.docx](#)]

Multimedia Appendix 3

Topic guide for people with lived experience of eating disorders.

[[DOCX File, 23 KB - xr_vli1e47382_app3.docx](#)]

Multimedia Appendix 4

Topic guide for clinicians.

[[DOCX File, 23 KB - xr_vli1e47382_app4.docx](#)]

Multimedia Appendix 5

Powerpoint images shown to participants.

[[PPTX File, 5103 KB - xr_vli1e47382_app5.pptx](#)]

Multimedia Appendix 6

Practicalities of delivering virtual reality therapy for people with eating disorders.

[[DOCX File, 17 KB - xr_vli1e47382_app6.docx](#)]

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Abbreviations

VR: virtual reality

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Original Paper

Enhancement of Immersive Technology Use in Pediatric Health Care With Accessible, Context-Specific Training: Descriptive Feasibility Study

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Abstract

Background: Immersive technology provides adjuncts for pediatric care. However, accessibility and inadequate training limit implementation of this technology. Standardized instruction with no-cost software licensing may improve health care professionals' facility with immersive technologies.

Objective: This descriptive feasibility study aimed to examine the applications of immersive technologies in pediatric health care, including virtual reality (VR) and projectors.

Methods: We developed immersive technology instructional guides for pediatric health care. The training guides were created for multiple software content and hardware types across several clinical scenarios. Content was available in print and digital versions. The primary outcome was technology use across sites with no-cost software agreements. The secondary outcome was the specific application types used at a single site, stratified by sessions and minutes. Data were analyzed using descriptive statistics.

Results: Data were collected from 19 licensed sites from January through June 2022. Among the 19 sites, 32% (n=6) used 10 or more VR units. Among the 6 sites that had projectors, half used 5 or more units. The mean minutes of use per month of all sites combined was 2199 (IQR 51-1058). Three sites had more than 10,000 minutes of total use during the 6-month review period. Secondary results indicated that active VR (977 total sessions) and passive projector streaming (1261 total sessions) were the most popular application types by session, while active projector (66,849 total minutes) and passive projector streaming (32,711 total minutes) were the most popular types when stratified by minutes of use. The active VR application with the most minutes of use was an application often used in physical therapy.

Conclusions: Context-specific technological instruction coupled to no-cost licenses may increase access to immersive technology in pediatric health care settings.

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KEYWORDS

immersive technology; implementation; adult learning; education; pediatric; accessibility; training; therapeutic; pediatric care; utilization; virtual reality; VR; monitoring; license; development; software; monitoring software

Introduction

Although immersive technologies are rapidly developing, their adoption in health care greatly varies due to differences in access and acceptability. Recent research has supported novel health care applications of immersive technologies such as virtual reality (VR) [1,2]. Differences in user backgrounds, including technological literacy and financial resources, remain access barriers for health care systems, creating a digital divide [3-5]. Although immersive technologies are not yet widely used, the market is growing quickly due to reduced costs and improved technology [6,7].

Despite the abundance of efficacy research of immersive technologies in health care, standardized strategies for effective implementation across multiple hospital settings are lacking. Immersive technologies may be adopted for a variety of clinical uses, including patient education, surgical planning, and rehabilitation [8-10]. VR also has analgesic properties, with distraction, focus-shifting, and skill-building identified as its mechanisms for reduced pain perception [11-15]. Given the opioid epidemic, the analgesic benefits of VR could be widely implemented as another tool to reduce the morbidity related to opioid misuse [16-20].

Andragogic learning theories provide the foundation for the development of tools to train health care professionals on how to best use immersive technologies [18-21]. Effective adult learning is guided by the principles of cognitive load engagement and active learning [21-24]. Adult learning theories suggest that short videos and multimedia presentations are more effective than traditional didactic lectures [25]. Lengthier video trainings have variable effects on long-term retention, whereas shorter, segmented videos improve recall [21,26,27]. The use of multimedia instruction, including web-based content, further engages adult learners [28,29].

Given the benefits of immersive technologies, we sought to integrate immersive technologies in pediatric health care settings with a standardized set of clinical guides coupled with no-cost software licensing. While developing learning materials, we remained cognizant of the recency of immersive technology, factors that influence immersive technology acceptance, and best practices to improve learning outcomes.

The primary aim of this descriptive feasibility study was to measure the utilization rate of immersive technologies in a variety of pediatric health care settings after the implementation of standardized training with no-cost software licenses. The secondary aim was to explore the types of immersive technology applications used at a single institution.

Methods

Context

This study was conducted as part of a research and clinical program at an academic children's hospital (Lucile Packard Children's Hospital Stanford [LPCHS]), focusing on the research, development, and validation of immersive technologies for use in pediatric health care [30]. Physicians who lead the program founded a federal, tax-exempt, nonprofit corporation.

The mission of the nonprofit is to distribute pediatric immersive technology applications to reduce anxiety, support rehabilitation, and promote pain perception reduction. This nonprofit also helps children with harm reduction, healthy choice education, and mental health support. The nonprofit works with researchers and health care professionals (including but not limited to physicians, nurse practitioners, registered nurses, child life specialists, and physical therapists) to create and distribute free software that is fun, nonviolent, non-nauseating, and practical for many clinical settings. In addition to providing no-cost software licenses, the nonprofit provides training to help these professionals embed immersive technology in clinical practice. Data for this study were collected from January through June 2022.

Hardware

VR applications distributed by the nonprofit use both portable hardware, including Oculus Go (Meta, Inc), Oculus Quest/Quest 2 (Meta, Inc), and Pico G2 (ByteDance, Ltd). The nonprofit also distributes projector-based applications that use the Nebula Capsule (Anker Innovations Co), a portable smart projector that displays visuals on a surface secured with a mounting clip [31,32].

Training

The training consisted of a series of instructional videos and step-by-step written instructions, available in print and in digital, web-based format. The nonprofit developed a novel framework for introducing and guiding pediatric patients through VR experiences. This framework contained 5 steps: screen, discuss, empower, coach, and clean (Figure 1). These 5 steps were adapted from adult learning theory to fit a health care context, the specific needs of a pediatric population, and the constraints of immersive technology experiences. The nonprofit designed the intervention to be sensitive to several factors: the cognitive load required of practitioners to learn a new skill in a high-risk environment, the plurality of pediatric patient health care needs and constraints, and the requirement to present immersive technologies to patients in a way that elicited their participation.

First, to remain sensitive to the occupational demands on practitioners' working memories, any intervention would need to respect these demands by the use of a sufficiently scaled information hierarchy. For example, the intervention would need to make only the vital information quickly accessible and only deliver new information as necessary. This was accomplished by creating separate guides according to use case, revealing actionable steps around a broadly applicable framework, and through a nested information hierarchy in the digital intervention materials. We further reduced the cognitive load on practitioners by prescribing as many directives for actions and sentence frames for dialogue as possible without tailoring those prescriptions too narrowly to a specific use case.

Second, the intervention needed to balance ease of accessibility with sufficient nuance to capture diverse patient needs. The content catered to the disparate uses of immersive technologies (ie, physical therapy, distraction from pain or fearful environments, and anesthesia induction), patient characteristics (ie, age, mobility, cognitive ability, level of comfort with VR,

quality of eyesight, body position requirements of certain procedures), and the needs of specific experiences (ie, dialogue prompts, experience-specific movements, level of difficulty).

Third, the intervention was designed to elicit patient engagement. Leveraging self-determination theory, the intervention emphasized agency and choice for patients in terms of their VR experience and the amount of information about the external environment they wanted to receive during the VR experience [33,34]. This was also accomplished by incorporating multiple decision points after receiving new information about the VR experience.

The medium consisted of static digital guides that could be printed or digitally referenced, video guides that demonstrated how to conduct a VR experience with patients with different health care goals in varied contexts, and a hierarchically nested digital library that included all resources in addition to descriptions of each immersive technology and their respective use case (Multimedia Appendix 1). Video guides detailed (1) how to use the equipment, (2) how to present the immersive technology intervention to patients, and (3) how to conduct each immersive experience (Multimedia Appendix 2). The guides were available to all licensed nonprofit users.

Figure 1. Excerpt from a learning guide.



Outcomes and Measures

The primary aim of this study was to measure the utilization rate of immersive technologies at institutions that licensed the software through the authors' nonprofit. The secondary aim was to analyze the use of different types of immersive technology applications at a single institution according to site-specific data. Applications were stratified by VR, projector, active, passive, or training. Use was measured by the number of sessions launched and total number of minutes engaged in an application. These data were not available from the entire cohort due to technological privacy related to the license.

Anonymized data were collected from a mobile device management dashboard (Manage XR). This allowed for the measurement of the type of applications (active vs passive), the length of time for which the application was used, and the number of sessions launched.

Analysis

Descriptive statistics were used to analyze the use of immersive technologies at the index institution (LCPHS) as well as at the sites to which the technologies were distributed. Results are reported as means and IQRs.

Ethical Considerations

The Stanford University Institutional Review Board provided a waiver of the requirement of approval owing to the use of historical data.

Results

Primary Outcome: Institutional Use

The software was licensed to 18 institutions in addition to LPCHS. Institutes were located across all 4 Census Bureau regions of the United States (4 in the Northeast, 4 in the Midwest, 5 in the South, and 3 in the West), in addition to 3 sites in Canada. The majority of users seeking license and training agreements were first-time or novice users. Although most (n=17) sites had fewer than 25 pieces of equipment, site

4 and LPCHS possessed over 50 types of equipment. Go and Quest/Quest 2 were the most commonly used equipment types at 34% (100/297) and 44% (131/297) of equipment totals, respectively (Figure 2). Thirteen sites did not have Nebula projectors available; all 6 sites that did have these projectors had at least the same number of VR devices as Nebula projectors (VR/projector ratio>1).

Equipment was variably used among institutions (Figure 3A-B). The mean of monthly usage was 2199 (IQR 51-1058) minutes across all sites combined (Figure 3A). Sites 4, 10, and LPCHS were notable for substantial use with an average of 3613 (IQR 1443-5202), 18,200 (IQR 15,249-23,293), and 5734 (IQR 4807-7252) monthly minutes, respectively (Figure 3B). Only 3 sites had more than 10,000 minutes of total usage across the review period.

Figure 2. Tye of immersive technology equipment available across sites. LPCHS: Lucile Packard Children’s Hospital Stanford.

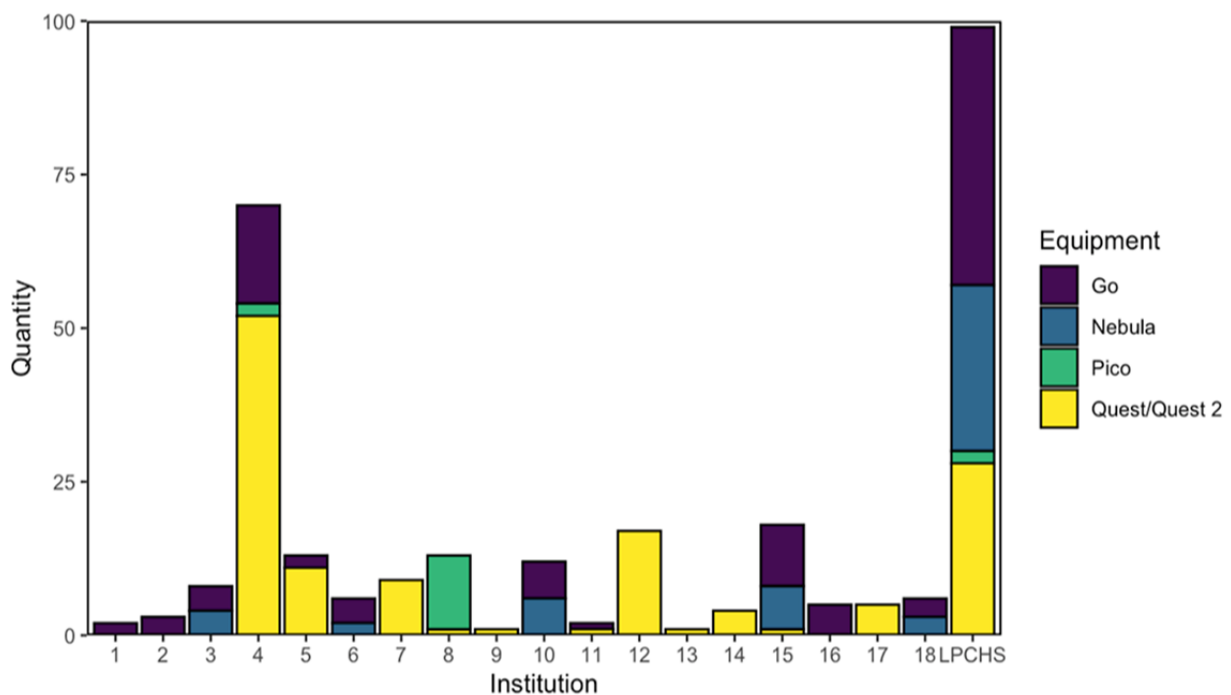
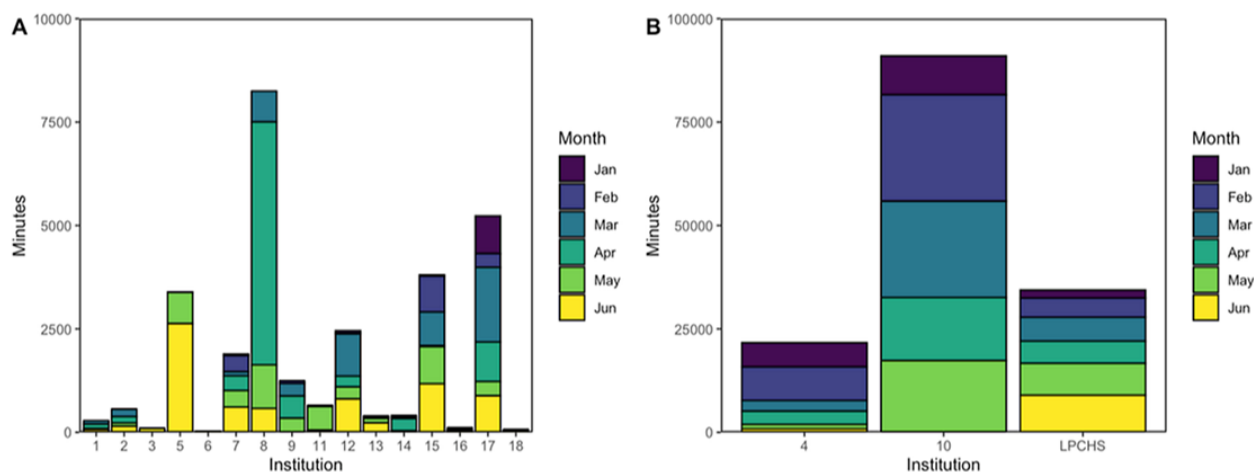


Figure 3. (A) Usage minutes over the review period by month and site for sites with ≤10,000 total minutes of use. (B) Usage minutes over the review period by month and site for sites with >10,000 total minutes of use. LPCHS: Lucile Packard Children’s Hospital Stanford.



Secondary Outcome: Types of Applications Used

The number of sessions and stratified application type increased over the review period at LPCHS (Figure 4). While the level of passive projector use remained consistent, there was an increase in active VR usage. Patients used active VR and passive projector media applications most commonly when analyzed by session count, with 977 and 1261 total sessions, respectively (Figure 4). Patients used active and passive projector streaming most commonly when usage was analyzed by minutes, with 66,849 and 32,711 minutes of use, respectively.

Analysis of specific applications revealed that most sessions of active VR applications were games, including Vacation Simulator (Owlchemy Labs), which accounted for 22%

(212/977) of all active VR sessions. The most-launched passive projector sessions were streaming services such as Netflix, accounting for 57% (720/1261) of all passive projector sessions (Figure 5).

The active VR application with the most minutes of use was an application often used to promote rehabilitation called The Climb 2 (Crytek) with 2815 minutes of use, accounting for 15% (2815/19355) of all active VR minutes. The most frequently used active projector application by minutes was an application designed to facilitate anesthesia induction called Sevo & Desi (Stanford Chariot Program), accounting for 85% (56,860/66,849) of active projector minutes. The most frequently used passive projector application was YouTube, accounting for 55% (18,133/32,711) of passive projector minutes (Figure 6A-B).

Figure 4. Types of applications at Lucile Packard Children’s Hospital Stanford. VR: virtual reality.

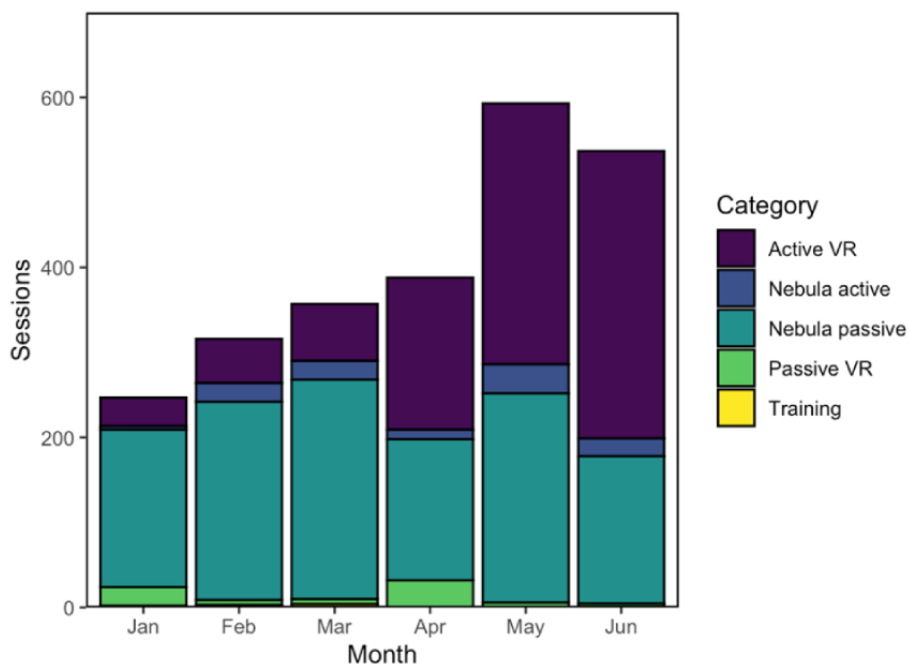


Figure 5. Sessions per application at Lucile Packard Children’s Hospital Stanford. VR: virtual reality.

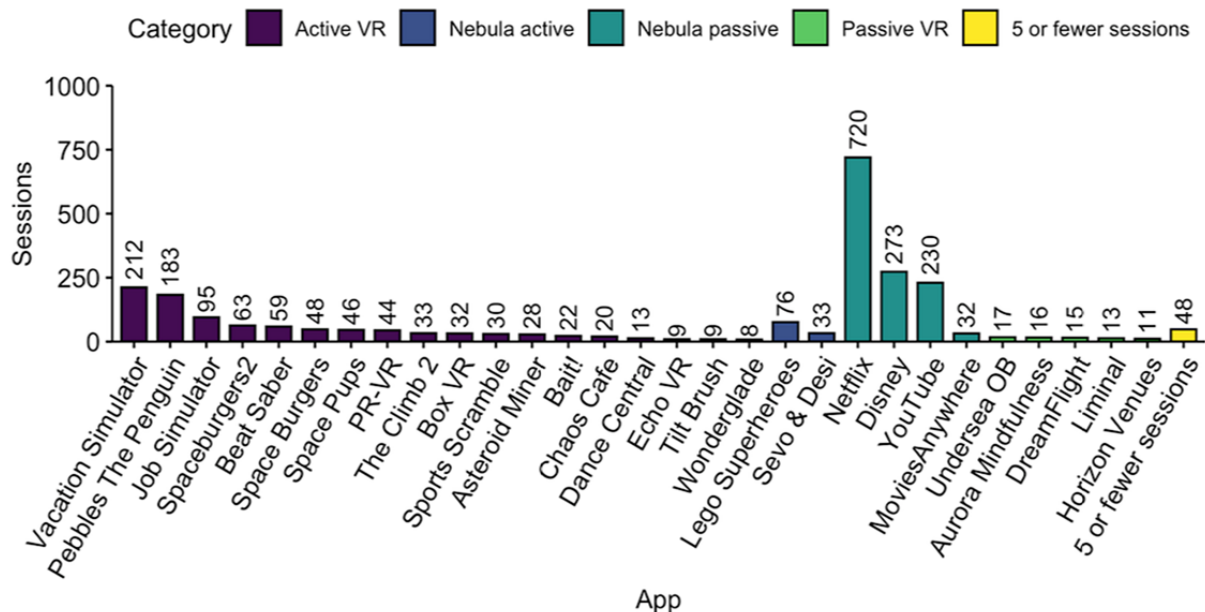
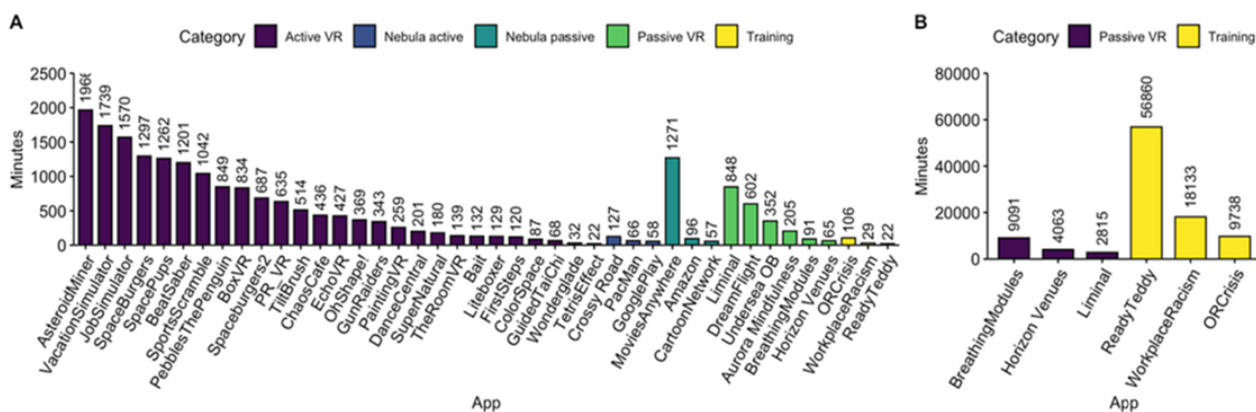


Figure 6. (A) Minutes of use per application with ≤2500 total minutes at Lucile Packard Children’s Hospital Stanford (LPCHS). (B) Minutes of use per application with >2500 total minutes at LPCHS. VR: virtual reality.



Discussion

Principal Findings

Immersive technologies can be widely disseminated with no-cost licenses and complementary training materials. This study identified variation in the quantity and format of immersive technologies used across each site. The extent of immersive technology use appears to be influenced by the amount of equipment available at each site; most sites had fewer than 25 units of equipment available.

Different hardware is used for different clinical applications in children of different ages. For example, portable VR units may be used for acute distraction at the bedside in older children, whereas projectors are ideal for distraction during patient transport, particularly for younger children. Owing to the different clinical uses among sites, we observed variations in the types of immersive technology units deployed at each site. For example, some institutes only had Go units, such as sites 1, 2, and 16. Many other sites did not have projector units available, limiting streaming options for patients. Most sites were lacking one or more equipment types. Only LPCHS was equipped with all 5 equipment types.

We did not observe any generalizable trends in usage minutes across sites during the 6-month observation period. Rather, monthly usage minutes tended to fluctuate. However, sites with greater monthly minutes tended to experience consistently greater usage across all months than sites with lower usage minutes. At LPCHS, active VR and passive projector media streaming applications were used more often than active projector, passive VR, and training applications, potentially due to the user reception and clinical use setting. Although the data lack information on clinical context, active VR may have been selected by health care professionals when patients needed more immersion and engagement, such as during a stimulating procedure. Technological instruction for hospital staff may have contributed to the increased use of active VR applications at LPCHS, which generally require more training than passive modalities.

Further analyses of the types of software applications used in the hospitals would complement the LPCHS institutional data. Of all application types, we observed the greatest use of active

VR and passive projector content. Whereas active VR and active projector applications generally consisted of a mix of content created by the LPCHS research program and commercially available applications, passive projector applications were more likely to be commercially available streaming services. There is a broad selection of immersive technology content available and further research will be needed to identify the optimal content for different clinical scenarios.

Strengths and Limitations

This study demonstrates the promise for the multi-institutional use of immersive technologies through evidence-based instructional methods. Numerous human factors studies have demonstrated similar outcomes in different domains, including agriculture, industrial organization, household technology use, and online learning [35-38]. This study extends these outcomes by demonstrating the feasibility of the widespread adoption of immersive technology within the pediatric health care setting. Using a teaching model that prioritizes efficient integration and user accessibility may be a key factor to bridge technology research and clinical use. Furthermore, when institutions are provided with technical instructions based on adult learning techniques, adoption may be improved.

This study had several limitations. First, prior to adoption, all users would have reported their familiarity with device use to better quantify the training effectiveness. However, given the primary goal of increasing use and the deleterious effects of surveys on motivation, we opted to not include a preassessment.

Second, privacy regulations and protections on patient information limited our ability to determine the clinical context associated with each instance of immersive technology use. Additionally, outside of LPCHS, the number of sessions and types of applications were not available for analysis due to privacy policies.

Third, while data on patient demographics and specific uses of each application would have increased our understanding of VR utility, the aim of this project was to demonstrate wide-scale use. The hardware and software licenses did not provide access to protected health information to ensure the cyber safety of users. It was outside the scope of this project to have research assistants collect information on patient and use contexts at the wide variety of institutes included. Unlike most VR studies that

demonstrate specific health care uses without attention to practical implementation, this study describes a means toward practical implementation. Despite the lack of an entire cohort of institutional data, the types of applications used at LPCHS provide important information on the natural clinical use of immersive technologies in a pediatric hospital.

Lastly, while we successfully identified and analyzed widespread adoption across sites, we were unable to obtain a staff-level assessment of user sentiments or demonstrate causality between training materials and utilization rates.

Future Directions

This study demonstrates that technological digital instruction can facilitate the use of immersive technology in a wide variety of pediatric health care settings. Such methods have the potential to increase user acceptability and to be adapted to the instructional context. Further research will focus on the efficacy of different educational tools during technology instruction with user-specific feedback. Additional efforts will be made to evaluate factors that influence the acceptability of immersive technologies through the customization of training methods at institutions.

Acknowledgments

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Data Availability

The data sets generated and/or analyzed during this study are available from the corresponding author on reasonable request.

Authors' Contributions

EW and TJC conceived, planned, and supervised the study. EW performed the main investigation. All authors contributed to, revised, approved, and are accountable for the final manuscript.

Conflicts of Interest

TJC, SR, KF, and EW are on the board of Invincikids, a nonprofit organization that seeks to distribute immersive technologies to improve pediatric care. They receive no compensation for their roles. ANB is the Executive Director of Invincikids. The Stanford Chariot Program has received philanthropic gifts from Meta, Inc and Magic Leap, Inc. All other authors have no conflicts to declare.

Multimedia Appendix 1

Digital app library materials (excerpt from website).

[[PNG File , 356 KB - xr_v1i1e56447_app1.png](#)]

Multimedia Appendix 2

Virtual reality physical therapy field guide (excerpt from website).

[[MP4 File \(MP4 Video\), 19607 KB - xr_v1i1e56447_app2.mp4](#)]

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Abbreviations

LPCHS: Lucile Packard Children's Hospital Stanford

VR: virtual reality

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Original Paper

Mobile Phone–Based Personalized and Interactive Augmented Reality Pictorial Health Warnings for Enhancing a Brief Advice Model for Smoking Cessation: Pilot Randomized Controlled Trial

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Abstract

Background: Augmented reality (AR) is a novel modality for promoting smoking cessation (SC). AR-visualized adverse consequences for education and smoking prevention have only been evaluated in nonsmokers in previous studies.

Objective: To assess the feasibility and preliminary effectiveness for SC of AR pictorial health warnings (PHWs) on cigarette packs.

Methods: We conducted a pilot randomized controlled trial in adult daily smokers in communities in Hong Kong. All participants received AWARD (ask, warn, advise, referral, do-it-again) model-guided SC advice, a warning leaflet, and referral to SC services at baseline. Interactive, chat-based SC support comprising regular messages and real-time support was provided to all participants via instant messaging apps (eg, WhatsApp) for 3 months after randomization. Participants in the intervention group additionally received 6 links to the AR PHWs showing the worsening health status of various organs caused by smoking. The level of the AR PHWs was adjustable to smoking behaviors (ie, smoking duration or daily cigarette consumption) to increase interaction. Participants could swipe, drag, or rotate the 3D PHWs to reinforce their impression of the health consequences of smoking. The primary outcome was self-reported past 7-day point-prevalence abstinence (PPA) at 3 months. The acceptability of the AR intervention was assessed by the proportion of participants who had viewed AR PHWs during the intervention. Participants who viewed AR PHWs further evaluated the perceived effect of the AR PHWs on a scale of 0 (not helpful at all) to 10 (very helpful). Intention to treat was used, and the risk ratio (RR) of the intervention effect was estimated by Poisson regression.

Results: From April to November 2021, 80 participants were recruited and randomly assigned to intervention (n=40) and control (n=40) groups. Most participants were male (66/80, 83%) and planned to quit beyond 30 days or were undecided (65/80, 81%). The intervention group had a higher but nonsignificant 7-day PPA (7/40, 18% vs 5/40, 13%; RR 1.40, 95% CI 0.48-4.07) and quit attempts (15/40, 38% vs 11/40, 28%; RR 1.36, 95% CI 0.71-2.60) at 3 months than the control group. In the intervention group, 17 of 40 (43%) participants viewed the AR PHWs. The AR PHWs had modest effects on knowledge of the adverse consequences of smoking on personal health (mean score 3.94, SD 3.52), reducing the frequency of buying cigarettes (mean score 3.29, SD 3.08), increasing the perceived importance of quitting (mean score 3.88, SD 3.50), and making the PHWs more disgusting (mean score 3.41, SD 3.08) and horrible (mean score 3.38, SD 3.05). The 3-month self-reported 7-day PPA was higher in those who ever (vs never) viewed the AR PHWs (5/17, 29% vs 2/23, 9%).

Conclusions: The mobile-based interactive AR PHWs were feasible, and the effectiveness on smoking abstinence warrants further testing.

Trial Registration: ClinicalTrials.gov NCT04830072; <https://clinicaltrials.gov/study/NCT04830072>

KEYWORDS

augmented reality; mobile-based; smoking cessation; brief advice; pictorial health warning; pilot randomized controlled trial

Introduction

Brief advice is effective in promoting smoking cessation (SC) [1-4]. Pictorial and text warnings on adverse smoking consequences are always used to warn smokers about the harms of continued smoking when delivering brief SC advice. Pictorial warnings evoke negative emotions about smoking [5] and increase quit attempts [6] and quit intentions [5]. However, the effects of pictorial and text warnings can be attenuated, since some smokers feel disconnected from the smoking-attributable diseases being shown [7,8]. Enhancing pictorial and text warnings is needed to strengthen their effect on promoting SC. Augmented reality (AR) technology, allowing interaction using vivid 3D visual imaging, has potential for promoting SC and could be promising.

A recent experimental study found that AR-visualized messages about adverse consequences of smoking increased negative emotions toward smoking and willingness to engage in an SC campaign in college students [9]. AR-simulated adverse consequences of smoking (eg, in the lungs) were used in educating nonsmokers about smoking hazards to the human body [10] and dissuading nonsmokers from smoking [11], but the effects were not assessed using a rigorous research design. Recent studies have suggested the potential of AR as a novel modality for conducting cue exposure therapy for SC (ie, extinguishing cue-provoked urges to smoke by exposure to smoking-related cues) since smoking-related AR images were found to have a similar effect on eliciting cue-provoked urges to smoke compared to in vivo smoking cues [12,13]. Our literature review of PubMed (up to September 2023) using the terms “augmented reality” and “smoking cessation” found no study assessing the effect of AR visualization of adverse consequences from smoking on SC. Therefore, a pilot study is needed to assess the feasibility of AR visualization of adverse consequences from smoking for SC to inform a larger-scale, full trial.

Hong Kong has a relatively low smoking prevalence (9.5% in 2021 [14]). However, significant increases in the proportion of smokers without an intention to quit (12.7% to 69%) or past quit attempts (74.4% to 80.4%) were observed from 2009 to 2018 [15]. The penetration of mobile phones in Hong Kong has provided a novel avenue for SC, considering that less-motivated smokers might be receptive to mobile-based intervention [16]. Several studies have shown that widely used mobile instant messaging (IM) apps (eg, WhatsApp, WeChat) are a promising modality for delivering personalized and interactive SC interventions [2,17,18]. Communicating smoking-related adverse consequences with texts or pictures via IM apps was also found to be feasible [18]. These findings suggest that IM apps might be usable to deliver AR for smokers, especially smokers with a lower quit intention who are less willing to download and use additional SC-related apps [19]. Pictorial health warnings (PHWs) on cigarette packs portraying the adverse consequences

of smoking and disseminating messages on quitting are widely and frequently seen by smokers (126 countries and jurisdictions finalized requirements for PHWs by 2021 [20]). Hong Kong introduced PHWs in 2007, and adopted 12 new PHWs with at least 85% coverage of the principal packaging of cigarettes in 2018. In Hong Kong, 88.6% of current smokers reported having seen PHWs in the past 30 days in 2018 [21]. This study used the notion that PHWs are widely viewed by the public on cigarette packaging and developed 6 new, localized, AR-based PHWs (Multimedia Appendix 1). Taking advantage of IM apps, this pilot study aimed to examine the feasibility and preliminary effect of AR PHWs on SC.

Methods

Ethical Considerations

Ethical approval was obtained from the institutional review board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (UW 21-018), and the trial was registered with ClinicalTrials.gov (NCT04830072). Written consent was obtained from all participants after informing them that they had the right to withdraw from the study at any time, and all the information collected was anonymized and was only used for research. After completing each follow-up, all participants were compensated with HK\$ 50 (US\$ 6.40). The Consolidated Standards of Reporting Trials (CONSORT) reporting guidelines and their extension to randomized pilot and feasibility trials were followed [22].

Study Design, Setting, and Participants

We conducted a parallel, 2-arm, pilot randomized controlled trial (RCT) in Hong Kong. From April to November 2021, participants were individually recruited at smoking hot spots (ie, places where smokers linger and smoke) in community sites. Research staff proactively approached smokers using a “foot-in-the-door” technique, which is commonly used in SC trials in the context of smokers with low intention to quit [1,2,23]. Briefly, the research staff initiated a conversation by asking about small and simple questions like their daily cigarette consumption and quit attempts. Those willing to talk were warned about the risk of continuous smoking and advised to quit smoking as early as possible. Smokers who expressed interest in SC were briefly introduced to the trial, screened for eligibility, and invited to join. Eligibility criteria included being Chinese, being a smoker, being aged 18 years or older, smoking at least 1 cigarette daily in the past 30 days, owning a smartphone with IM apps (eg, WhatsApp), and being able to communicate in Chinese. We excluded smokers who were participating in other SC services or projects.

Randomization and Blinding

Participants were individually randomized to intervention or control groups (at a 1:1 ratio) according to a predefined randomization list with permuted block sizes of 2, 4, and 6. The

allocation sequence was generated by a noninvestigator and was concealed from the research staff involved in participant recruitment. To avoid treatment contamination, we only recruited 1 smoker at 1 smoking hot spot at 10-minute intervals. Blinding of participants and the SC advisor who delivered the interventions was not possible. All outcome assessors and statistical analysts were blinded to treatment allocation until the primary analyses were completed.

Interventions

All participants received brief SC advice following the AWARD (ask, warn, advise, referral, do-it-again) model [1-3] and were offered referrals to SC services at baseline. As a widely adopted alternative practice for smokers who are less ready to quit in SC programs [2,24], chat-based SC support was delivered to all participants for 3 months via IM apps (ie, WhatsApp). Guided by motivational interviewing (MI) techniques [25] and the transtheoretical model [26], the chat-based SC support included prescheduled messages and real-time support personalized to the quitting process provided by 1 SC advisor (a registered nurse trained in SC treatments and MI techniques). The 24 prescheduled messages' content and frequency were adjusted according to participants' willingness to quit at baseline based on the transtheoretical model (willing to quit within 30 days/after 30 days or undecided) [26]. For participants willing to quit within 30 days, the messages covered quitting strategies, coping skills, and encouragement. Participants who were not ready to quit within 30 days received messages on motivational advice, benefits of SC, hazards of smoking (and secondhand smoke), and encouragement. At least 1 message was delivered per week to initiate the conversation between participants and the SC advisor. The frequency of the prescheduled messages increased to 2 to 3 per week when approaching the quit date set by the participant. The real-time support was also personalized to participants' inquiries and followed MI techniques to enhance motivation and self-efficacy of quitting. The SC advisor discussed the supporting content with experts in the SC team when necessary.

Six web AR links were integrated into the messages during the chat-based SC support for the intervention group. The AR links were built based on 6 of 12 local PHWs (due to the limited budget; [Multimedia Appendix 1](#)): "smoking takes away my voice," "smoking causes "lung cancer," "smoking causes peripheral vascular disease," "smoking causes impotence," "smoking causes aging," and "smoking offence: fixed penalty HK \$1500." These 6 PHWs were chosen because they were particularly suitable for using 3D animations to show the disease's progression and the increasing cost of smoking. One

AR technology company developed the AR links with the SC experts' continuous comments on the shape and color of the models and necessary changes. All the AR PHWs were designed to increase the participants' awareness of the devastating effects on health of smoking and its ever-growing monetary cost, thereby promoting their engagement in the chat-based SC support. The AR PHWs could be accessed by using the smartphone's camera and the mobile web browser on the 2 most widely adopted mobile operating systems, iOS and Android, without the requirement to download any apps.

The web AR links were opened in a mobile web browser, and the participants were instructed to scan the corresponding PHWs to activate the AR links. Upon successfully scanning the PHWs, they were shown jointly with the corresponding augmented components (ie, 3D PHWs and texts) on the screen. Participants could interact with the augmented components and real-world images at the same time. By default, 30-second 3D animations of the PHWs were played to show the gradually worsening health status of organs (eg, changes in the color and shape of the lungs) because of continuous smoking. The corresponding health status of the organs was displayed in 3D when inputting smoking behaviors (ie, smoking duration or daily cigarette consumption). The 3D PHWs showing the status of the organs could be swiped, dragged, or rotated to be viewed from different angles. Participants could also interact with the 3D PHWs by dragging the horizontal scroll bar to indicate different durations of smoking (or levels of cigarette consumption) to see the changing status of the organs (the AR PHW for "smoking causes peripheral vascular disease" is shown in [Figure 1](#)). The original PHW for "smoking offence: fixed penalty HK \$1500" used images of money to warn smokers that smoking in smoke-free areas has a fine of HK \$1500 (US \$192.30). To keep consistency with other AR PHWs that show changes in organs due to smoking, we redesigned this PHW to show the amount of money spent yearly based on daily cigarette consumption and the average price of a pack of cigarettes (HK\$ 60; US \$7.70) at the time of the study. When activated, the animation showed an increasing amount of money being burned due to smoking. The feeling of holding the 3D PHWs in their hands and viewing them from different angles might remind participants of the corresponding PHWs naturally and intuitively. The SC advisor also encouraged participants to click the links and interact with the AR PHWs and supplemented the information (eg, with corresponding PHWs or a brief introduction) as appropriate. As an alternative way to access the AR PHWs, we provided the PHW images on a separate device (eg, a personal computer running WhatsApp) so that the users could scan the images with their mobile phones.

Figure 1. Example of pictorial health warning (PHW) and corresponding augmented reality PHW.

PHW: smoking causes peripheral vascular disease

Example of 3D animation progress

Input smoking duration

Corresponding status
Scrolling to see the changed status

Measures

At baseline, we collected sociodemographic characteristics (sex, age, education, monthly household income, and employment status), smoking and quitting behaviors (daily cigarette consumption, nicotine dependency level [27], past quit attempts, willingness to quit, and self-efficacy [2]). The nicotine dependency level was measured by the Heaviness of Smoking Index (HSI), which sums up the scores of 2 questions: the number of cigarettes smoked per day and the time to the first cigarette after waking. Total HSI scores of ≤ 2 , 3-4, and 5-6 indicate low, moderate, and high levels of nicotine dependency, respectively. The willingness to quit was measured by asking participants their planned quit date with responses of “within 7 days/30 days/60 days/undecided.”

Telephone follow-ups were conducted at 1 month and 3 months after intervention initiation. The primary outcome was self-reported 7-day point-prevalence abstinence (PPA) at the 3-month follow-up. Secondary outcomes included the 7-day PPA at the 1-month follow-up, smoking reduction by at least 50% of baseline daily cigarette consumption (excluding quitters), and quit attempts (defined by abstinence for at least 24 hours) at the 1- and 3-month follow-ups.

Considering that proactive recruitment and chat-based support via IM apps have shown feasibility in our previous SC studies [1,2,17,28], we calculated the proportion of participants who had viewed the AR PHWs during the intervention to assess the acceptability of the AR intervention component. The proportion was defined as the actual number of participants who reported having ever viewed the AR PHWs at the follow-ups divided by the number of participants in the intervention group. Missing values were treated as “no viewing.” In participants who viewed the AR PHWs, we further evaluated the perceived effect of the AR PHWs on (1) knowing the adverse consequences of smoking on personal health, (2) increasing the perceived importance of quitting, (3) reducing the frequency of buying cigarettes, (4) perceiving PHWs as more disgusting, and (5) perceiving PHWs as more horrible, each on a scale of 0 (not helpful at all) to 10 (very helpful).

Sample Size Calculation

No formal sample size calculation was conducted. The sample size of 80 participants is comparable with previous studies of

virtual reality interventions (ranging from 8-102 [29]) for SC and was deemed sufficient to test the feasibility and estimate the parameters to inform the design of a definitive RCT.

Data Analyses

We compared the primary and secondary outcomes between the 2 groups using Poisson regression with robust variance [30], which yielded risk ratios (RRs) of the intervention effect. The model was further adjusted for imbalanced baseline characteristics (ie, education) as a sensitivity analysis. The intention to treat approach was adopted, assuming participants lost to follow-up did not change their smoking behaviors (eg, they made no quit attempts nor changed their daily cigarette consumption) [31]. The acceptability and perceptions of the AR PHWs were reported descriptively using the proportion of participants (%) or mean (SD) as appropriate. Post hoc analyses assessed the difference in 3-month self-reported abstinence, smoking reduction, and quit attempts in the intervention group among those who had ever viewed the AR PHWs and those who had not. All analyses were conducted in Stata/MP (version 15.1; StataCorp). A 2-sided P value $<.05$ was considered statistically significant.

Results

Eighty participants were randomized to the intervention ($n=40$) and control ($n=40$) groups (Figure 2). Table 1 shows that 83% (66/80) of participants were male, 33% (26/80) were aged 50 years or above, and 65% (52/80) had secondary education or less. At baseline, 65% (52/80) had a low level of nicotine dependence, and 81% (65/80) planned to quit beyond 30 days (or were undecided). Baseline characteristics were similar between the 2 groups, except that more participants in the intervention group had tertiary education ($P=.005$). The follow-up retention rates were 74% ($n=59$) at 1 month and 68% ($n=54$) at 3 months; this was similar between the groups ($P=.15$ and $.90$).

Table 2 shows that the intervention group had a slightly higher but not statistically significant self-reported 7-day PPA (7/40, 18% vs 5/40, 13%; RR 1.40, 95% CI 0.48-4.07) and quit attempts (15/40, 38% vs 11/40, 28%; RR 1.36, 95% CI 0.71-2.60) than the control group at 3 months. Similar outcomes were observed after adjusting for levels of education.

Participants in the control group had a higher smoking reduction rate compared to participants in the intervention group after excluding quitters, but the difference was not statistically significant at 3 months (4/33, 12% vs 8/35, 22%; RR 0.50, 95% CI 0.16-1.54).

Table 3 shows that 17 of 40 (43%) participants in the intervention group viewed the AR PHWs. Participants who viewed the AR PHWs rated them as having a mild effect on knowing the adverse consequences of smoking on personal health (mean rating 3.94, SD 3.52), reducing the frequency of buying cigarettes (mean rating 3.29, SD 3.08), perceiving an increase in the importance of quitting (mean rating 3.88, SD

3.50), finding PHWs more disgusting (mean rating 3.41, SD 3.08), and finding PHWs more horrible (mean rating 3.38, SD 3.05).

Table 4 shows the results from a post hoc analysis on viewing AR pictures and SC outcomes in the intervention group. The 3-month self-reported 7-day PPA was higher in those who ever (vs never) viewed AR PHWs (5/17, 29% vs 2/23, 9%). Similar results were observed for quit attempts at 3 months (8/17, 47% vs 7/23, 30%). The participants' characteristics were similar regardless of ever viewing the AR PHWs (Multimedia Appendix 2).

Figure 2. Trial flow chart.

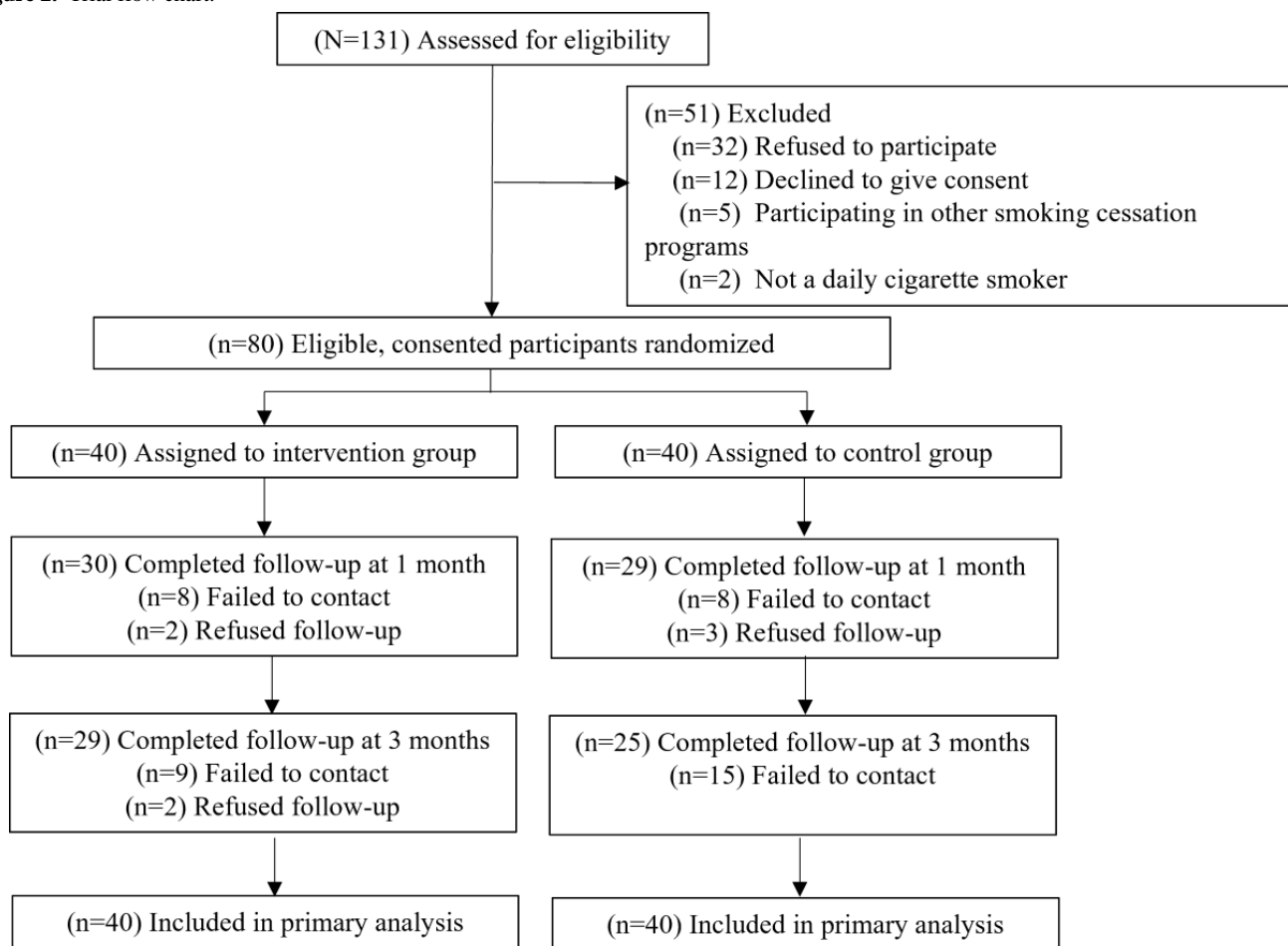


Table 1. Participants' characteristics at baseline (n=80).

| Characteristics | Intervention group (n=40) | Control group (n=40) | P value ^a |
|---|---------------------------|----------------------|----------------------|
| Sex, n (%) | | | .24 |
| Male | 31 (78) | 35 (88) | |
| Female | 9 (23) | 5 (13) | |
| Age (years), n (%) | | | .78 |
| 18-29 | 8 (20) | 5 (13) | |
| 30-39 | 9 (23) | 9 (23) | |
| 40-49 | 10 (25) | 13 (33) | |
| ≥50 | 13 (33) | 13 (33) | |
| Education, n (%) | | | .005 |
| Secondary or below | 20 (50) | 32 (80) | |
| Tertiary | 20 (50) | 8 (20) | |
| Monthly household income (US \$1=HK \$7.80), n (%) | | | .26 |
| ≤\$19,999 | 7 (26) | 13 (41) | |
| \$20,000-\$29,999 | 5 (19) | 8 (25) | |
| >\$30,000 | 15 (56) | 11 (34) | |
| Employment^b, n (%) | | | >.99 |
| Economically inactive | 4 (10) | 3 (8) | |
| Economically active | 36 (90) | 37 (93) | |
| Marital status, n (%) | | | .88 |
| Single | 16 (40) | 15 (38) | |
| Married | 21 (53) | 23 (58) | |
| Divorced or widowed | 3 (8) | 2 (5) | |
| Living with a child younger than 18 years, n (%) | | | .48 |
| No | 28 (70) | 25 (63) | |
| Yes | 12 (30) | 15 (38) | |
| Daily cigarette consumption, mean (SD) | 12.31 (7.10) | 11.31 (6.50) | .51 |
| Nicotine dependency level^c, n (%) | | | .82 |
| Light | 25 (63) | 27 (68) | |
| Moderate | 14 (35) | 13 (33) | |
| Heavy | 1 (3) | 0 (0) | |
| Past quit attempt, n (%) | | | .17 |
| Within past 1 month | 1 (3) | 5 (13) | |
| Within past 6 months | 12 (30) | 5 (13) | |
| Within past 1 year | 1 (3) | 3 (8) | |
| More than 1 year | 12 (30) | 12 (30) | |
| Never | 14 (35) | 15 (38) | |
| Willingness to quit, n (%) | | | .24 |
| Within 7 days | 4 (10) | 6 (15) | |
| Within 30 days | 1 (3) | 4 (10) | |
| Within 60 days | 2 (5) | 1 (3) | |
| Within 6 months | 3 (8) | 0 (0) | |

| Characteristics | Intervention group (n=40) | Control group (n=40) | P value ^a |
|--|---------------------------|----------------------|----------------------|
| Undetermined | 30 (75) | 29 (73) | |
| Self-efficacy, mean (SD)^d, n (%) | | | |
| Perceived confidence of quitting | 5.30 (2.57) | 5.43 (2.22) | .82 |
| Perceived difficulty of quitting | 6.60 (2.31) | 6.60 (2.04) | >.99 |
| Perceived importance of quitting | 4.83 (2.71) | 5.13 (2.27) | .59 |

^aP values were calculated with the χ^2 test or Fisher exact test for categorical variables and a 2-tailed *t* test for continuous variables.

^bEconomically active: employed or self-employed; economically inactive: student, housekeeper, retired, or unemployed.

^cMeasured by the Heaviness of Smoking Index (HSI): HSI score ≤ 2 =light; HSI score 3-4=moderate; HSI score 5-6=heavy.

^dScore range 0-10; higher scores indicate higher perceived importance, confidence, and difficulty of quitting.

Table 2. Smoking cessation outcomes in intervention vs control groups (N=80)^a.

| | Intervention (n=40), n (%) | Control (n=40), n (%) | Cohen ω | Risk ratio (95% CI) | P value | Adjusted risk ratio ^b (95% CI) | P value |
|--------------------------------------|----------------------------|-----------------------|----------------|---------------------|---------|---|---------|
| Self-reported PPA^c | | | | | | | |
| 1 month | 1 (3) | 3 (8) | 0.11 | 0.33 (0.04-3.11) | .34 | 0.35 (0.06-2.03) | .24 |
| 3 month | 7 (18) | 5 (13) | 0.07 | 1.40 (0.48-4.07) | .54 | 1.17 (0.40-3.39) | .78 |
| Smoking reduction^d | | | | | | | |
| 1 month | 3 (8) | 5 (14) | 0.08 | 0.60 (0.15-2.36) | .47 | 0.80 (0.22-2.95) | .74 |
| 3 month | 4 (12) | 8 (22) | 0.14 | 0.50 (0.16-1.54) | .23 | 0.47 (0.14-1.58) | .22 |
| Quitting attempts | | | | | | | |
| 1 month | 10 (25) | 11 (28) | 0.06 | 0.91 (0.43-1.91) | .80 | 0.92 (0.42-2.00) | .84 |
| 3 month | 15 (38) | 11 (28) | 0.91 | 1.36 (0.71-2.60) | .35 | 1.30 (0.65-2.48) | .49 |

^aMissing observations were treated as not quitting or reducing.

^aAdjusted for education.

^cPPA: point-prevalence abstinence.

^dAt least a 50% reduction in baseline daily cigarette consumption; participants who self-reported quitting were excluded.

Table 3. Viewing augmented reality (AR) pictures during the intervention period and perceptions of AR pictures (n=40)^a.

| | Values |
|---|-------------|
| Viewing AR pictures, n (%) | |
| Never viewed ^a | 23 (58) |
| Viewed | 17 (43) |
| “AR pictures can help to...” (ratings of perceptions), mean (SD) | |
| Know the adverse consequences of smoking on personal health | 3.94 (3.52) |
| Increase the perceived importance of quitting | 3.88 (3.50) |
| Reduce the frequency of buying cigarettes | 3.29 (3.08) |
| Perceive pictorial health warnings as more disgusting | 3.41 (3.08) |
| Perceive pictorial health warnings as more horrible | 3.38 (3.05) |

^aMissing observations were treated as never having viewed the AR pictures.

Table 4. Smoking cessation outcomes at 3 months by whether participants had viewed the augmented reality (AR) pictures during the intervention period in the intervention group (n=40)^a.

| | Never viewed AR pictures (n=23), n (%) | Viewed AR pictures (n=17), n (%) | P value |
|--------------------------------|--|----------------------------------|---------|
| Self-reported PPA ^b | 2 (9) | 5 (29) | .11 |
| Smoking reduction ^c | 3 (13) | 1 (6) | .43 |
| Quit attempts | 7 (30) | 8 (47) | .28 |

^aMissing observations were treated as never having viewed the AR pictures.

^bPPA: point-prevalence abstinence.

^cAt least a 50% reduction in baseline daily cigarette consumption; participants who self-reported quitting were excluded.

Discussion

Principal Findings

This is the first pilot RCT of mobile-based AR PHWs for SC in community smokers, showing that this approach was feasible and increased self-reported abstinence and quit attempts when provided on top of chat-based SC support. The 3-month 7-day PPA in the intervention (18%) and control (13%) groups in this study was comparable to that (15%) in our previous chat-based intervention for SC in 1185 smokers [2]. Notably, a direct comparison is not appropriate because of differences in the participants' characteristics and the intervention. Our study adds to the literature on the potential of AR for SC.

Despite most of the participants having low willingness to quit at baseline, nearly half (17/40, 43%) of the intervention group participants viewed the AR PHWs. This might be due to the attractiveness of the novel AR modality and demonstrates the feasibility and acceptability of delivering AR intervention through mobile phones to community smokers. AR can vividly show the progression of diseases caused by smoking in an immersive, interactive manner, which might improve viewers' acceptance of the warning information. Future mobile health (mHealth) SC interventions can involve AR as one component to attract and engage participants; mHealth interventions have been reported to have suboptimal engagement [32,33]. Notably, our AR links required scanning 6 types of PHWs on cigarette packs to activate the augmentation. Cigarettes with 12 types of PHWs are displayed in retail stores randomly, and participants bought cigarettes according to their preferences. Each type of package thus had a set PHW, and PHWs from other cigarette packages were lacking, which might have led to some AR PHWs not being activated or viewed. Even though we supplemented the PHWs in the chat-based SC support to mitigate this, supplementation required another device to display these PHWs to enable the activation of the AR content. These factors might have lowered the use of AR in this study. Future web AR content can be further designed with a function to scan pictures stored in the gallery on the users' phones to reduce the burden of requiring another device or picture.

Participants rated the effect of AR PHWs on reducing how many times they bought cigarettes and the effect of evoking disgust and horrible feelings as mild. Our prior territory-wide survey after the implementation of new and enlarged PHWs found that most current smokers in Hong Kong were not considering quitting (69%) or deferring smoking (89.2%) after noticing

PHWs [21]. Local PHWs have not been changed since 2018, and the warning effect of PHWs may be further diminished as a result of repeated viewing [34]. This might have weakened the perceived effect of our local PHW-based AR content on SC and eliciting negative emotions. Further AR content design can be refined by visualizing other adverse consequences of smoking. Apart from showing the deterioration of the organs, which might be familiar to smokers, using AR to show the mechanisms of smoking-related diseases at the microscopic level can be evaluated further. Prior studies have suggested AR can increase antismoking message acceptance by enhancing spatial presence (eg, the feeling of being there) and negative emotions [9,35]. Audio effects (eg, sound and music) to enhance immersion should be included to enhance the effect of AR.

Despite a perceived mild effect, we still observed more smoking abstinence (29% vs 9%) and quit attempts (47% vs 30%) in participants who viewed the AR PHWs compared to those who never did so. Most smokers understand the hazards of smoking but feel self-exemption from the adverse consequences of smoking [8,36]. Our AR was tailored to smoking behaviors, and the participants perceived relatively greater effects on understanding the adverse consequences of smoking on personal health and increasing the perceived importance of quitting. The AR PHWs might help participants connect adverse consequences of smoking with their own smoking behaviors to facilitate quitting.

Our finding of higher, but not statistically significant, smoking abstinence and quit attempts associated with the AR links combined with chat-based SC support could be due to a small sample size, which reduces the power to detect a statistically significant difference [37]. Since community smokers who are unmotivated to quit are less likely to download an SC app [38], we delivered AR links using instant messaging apps. The control group was offered chat-based SC support with similar content and intensity and a similar platform as the attention control. Since chat-based SC support is not usual care and may increase abstinence [2], adopting a strong effectiveness comparison may lead to underestimating the effect of AR PHWs on SC in the real world.

Limitations

This study has some limitations. First, some baseline characteristics were imbalanced, which is common in small-sample trials [22]. Similar results were also observed after adjusting for the imbalances. Second, although a previous study has shown that a proactive recruitment approach can recruit

smokers with demographic and smoking characteristics that are similar to those of general smokers in Hong Kong [39], the participants in this study were younger and more likely to have ever attempted to quit than general smokers (Multimedia Appendix 3). This difference, which might be due to the small sample size in this study, lowers the generalizability of the study findings. Additionally, most participants were male, which was in line with the sex distribution of smokers in Hong Kong [14]. Whether our findings can be generalized to other populations with more female smokers is uncertain. Third, abstinence may have been overreported without biochemical validation. But self-reports of abstinence were more feasible to obtain during the COVID-19 pandemic, and overreporting should have been similar in both groups. Fourth, this pilot study was underpowered to detect the effectiveness of mHealth-based AR PHWs on SC, and although our analysis of the intervention effect on smoking abstinence can be used to generate estimators for a full trial, our results cannot be interpreted as evidence for clinical practice. Fifth, data on the average number of AR PHWs each participant ever viewed were lacking, which might impede the exploration of the association between the dose of AR PHWs and SC. Sixth, the development of the AR PHWs did not involve smokers, which might affect the perception of the AR content

in the intervention and its utility. Posttrial qualitative interviews are warranted to refine the AR content design.

Implications

Considering that previous AR interventions for SC have always adopted a face-to-face approach [13], our findings provide initial evidence to support the feasibility of delivering AR interventions with a mobile modality. If the fully powered trial confirms the effect of the refined AR PHWs on smoking abstinence, mobile-based AR PHWs could be implemented to intervene in smoking behaviors. With the high accessibility of mobile phones, mobile-based AR interventions have the potential to be scalable in the real world, even in remote and resource-poor settings. These findings could also inform the development of mobile-based AR interventions for other harmful behaviors.

Conclusion

We showed the initial feasibility of mobile-based interactive AR content and preliminary evidence on its effectiveness on smoking abstinence. Further AR interventions can consider enhancing participants' immersive experiences and showing other adverse smoking-related consequences to maximize the effect on SC.

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Data Availability

The data sets in this study are available from the corresponding author on reasonable request.

Authors' Contributions

ZG contributed to project administration, software, formal analysis, methodology, visualization, and writing (original draft, review, and editing). YW contributed to conceptualization, resources, data curation, funding acquisition, validation, visualization, and writing (review and editing). MPW contributed to conceptualization, funding acquisition, supervision, and writing (review and editing). All authors approved the final version of manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Six pictorial health warnings on cigarette packs in Hong Kong.

[DOCX File, 2781 KB - [xr_v1i1e52893_app1.docx](#)]

Multimedia Appendix 2

Characteristics of intervention group participants divided by whether they viewed the augmented reality pictorial health warnings (n=40).

[DOCX File, 17 KB - [xr_v1i1e52893_app2.docx](#)]

Multimedia Appendix 3

Comparisons of the characteristics of the participants in this study and general smokers in Hong Kong.

[DOCX File, 16 KB - [xr_v1i1e52893_app3.docx](#)]

Multimedia Appendix 4

CONSORT-eHEALTH checklist (V 1.6.1).

[PDF File (Adobe PDF File), 92 KB - [xr_v1i1e52893_app4.pdf](#)]

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Abbreviations

- AR:** augmented reality
- AWARD:** ask, warn, advise, referral, do-it-again
- CONSORT:** Consolidated Standards of Reporting Trials
- HSI:** Heaviness of Smoking Index
- IM:** instant messaging
- mHealth:** mobile health

MI: motivational interviewing
PHW: pictorial health warning
PPA: point-prevalence abstinence
RCT: randomized controlled trial
RR: risk ratio
SC: smoking cessation

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Original Paper

Assessing Predictive Factors of Attitudes Toward Peer-Supported Mental Health Interventions in the Metaverse: Mixed Methods Study

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Abstract

Background: The metaverse is a promising avenue for accessible, effective digital mental health treatments. However, general attitudes toward peer-supported metaverse mental health interventions (MMHIs) remain largely unexplored.

Objective: This study examined the relation of sociodemographic, mental health, and technology factors in predicting attitudes toward MMHIs.

Methods: We used a mixed methods design with a self-report online survey (N=545 participants) to assess participant attitudes toward MMHIs and sociodemographic, mental health, and technology factors. Ordinal logistic regression was used to examine predictors of general interest in peer-supported MMHIs and binary logistic regression to examine predictors of preference for MMHIs versus face-to-face interventions. Inductive content analysis was performed on 483 open-ended responses regarding intervention preference.

Results: Older age (odds ratio [OR] 1.03, 95% CI 1.02-1.05; $P<.001$), higher ethnic identity centrality (OR 1.44, 95% CI 1.25-1.66; $P<.001$), more positive mental help-seeking attitudes (OR 1.22, 95% CI 1.06-1.42; $P=.007$), more online video game use (OR 1.26, 95% CI 1.09-1.44; $P=.001$), and greater virtual reality experience (OR 1.55, 95% CI 1.28-1.90; $P<.001$) were associated with greater odds of reporting more interest in MMHIs. Internet access was associated with greater odds of reporting less interest in MMHIs (OR 0.50, 95% CI 0.30-0.84; $P=.01$). Hispanic ethnicity (OR 1.81, 95% CI 1.13-2.90; $P=.01$), older age (OR 1.04, 95% CI 1.02-1.05; $P<.001$), higher ethnic identity centrality (OR 1.28, 95% CI 1.09-1.51; $P=.003$), smartphone access (OR 10.46, 95% CI 2.87-50.71; $P<.001$), higher self-reported video game use (OR 1.25, 95% CI 1.05-1.48; $P=.01$), and more positive computer attitudes (OR 1.05, 95% CI 1.01-1.10; $P=.02$) predicted greater odds of preference for MMHIs (versus face-to-face interventions), whereas the male gender (OR 0.43, 95% CI 0.28-0.68; $P<.001$), internet access (OR 0.12, 95% CI 0.02-0.40; $P=.002$), more positive mental help-seeking attitudes (OR 0.76, 95% CI 0.62-0.92; $P=.005$), and moderately severe (OR 0.20, 95% CI 0.07-0.51; $P=.001$) and severe (OR 0.26, 95% CI 0.08-0.79; $P=.02$) levels of depression symptoms predicted lower odds of preference for MMHIs. Qualitative analysis revealed 14 themes describing reasons for intervention preference. Anonymity (133/483, 27.5%), social aversion (38/483, 7.9%), ease of use and accessibility (35/483, 7.2%), anxiety (28/483, 5.8%), and comfort (26/483, 5.4%) tended to be endorsed by those preferring MMHIs. Ecological validity of social interactions (99/483, 20.5%), ecological validity of interventions (75/483, 15.5%), aversion/distrust toward technology (42/483, 8.7%), impersonal quality (31/483, 6.4%), and immersion/engagement (11/483, 2.3%) tended to be endorsed by those who preferred face-to-face interventions. Mental health attitudes (28/483, 5.8%), privacy (19/483, 3.9%), and miscellaneous reasons (46/483, 9.5%) were endorsed equally between preferences. Novelty (21/483, 4.3%) was most cited by those who expressed no preference.

Conclusions: This study identified several factors associated with attitudes toward peer-supported MMHIs, which may be leveraged to inform mental health outreach to interested populations.

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KEYWORDS

metaverse; mental health intervention; consumer attitude; digital mental health intervention; virtual world

Introduction

Background

In efforts to connect mental health services with those in need, novel technologies are increasingly used to facilitate mental health treatment. Recently, there has been significant development in the technology of the metaverse and its implications for the future of health care [1,2]. The metaverse, a collection of enduring, interoperable 3D virtual worlds in which people interact with each other and the environment using virtual avatars [3], shows promise as a platform for mental health interventions for several reasons. First, metaverse mental health interventions (MMHIs) are situated *between* technology-based interventions (which use technology to create unique therapeutic affordances) and mere technology-facilitated interventions (eg, psychotherapy delivered by video calls) [4]. This is because MMHIs use customizable, anonymous avatars to mediate social communication, which may appeal to individuals who would otherwise not seek treatment due to stigma, anxiety, or fear of discrimination in face-to-face therapy [5-8]. Second, MMHIs share many of the advantages of the wider umbrella of digital mental health interventions (DMHIs), including a controlled environment with integrated data collection and accessibility from a range of devices and locations [9]. Third, the social aspect of the metaverse offers simple integration of peer support programs [8]. Research suggests online peer support to be associated with improved depression symptomatology [10,11] and general peer support with increased engagement and efficacy in internet therapies [12].

The investigation of attitudes toward peer-supported MMHIs is critical to their development because it will aid in the identification of populations for whom MMHIs may facilitate mental help-seeking, as well as of barriers to seeking out these types of interventions. We are not aware of any research assessing factors that may influence attitudes toward MMHIs, but the broader literature on DMHIs suggests several factors that may have a significant impact on attitudes toward MMHIs.

Sociodemographic Factors

Research assessing the associations between common sociodemographic factors and attitudes toward DMHIs presents mixed results. For example, previous studies evaluating attitudes toward DMHIs report conflicting results as to whether associations with gender or age exist, as well as the direction of the associations found [13-17]. However, because the umbrella of interventions that can be defined as DMHIs is broad, these studies assess different interventions, from online peer support groups [13] to online psychotherapy delivered by a professional [17]. The investigation of attitudes toward peer-supported MMHIs is narrow in scope, which may aid in accuracy in identifying the relationships between relevant sociodemographic factors and attitudes toward peer-supported MMHIs. In addition, several key sociodemographic factors that could be associated with attitudes toward MMHIs have not been previously evaluated in the DMHI literature. Technological

access variables, such as internet access, are negatively associated with self-reported poor mental health [18] and could have a relationship with how one perceives the accessibility, pricing, or usability of technology-based MMHIs. Lastly, ethnic identity centrality (the importance one's ethnicity has to their identity as a whole) could play a role in attitudes toward MMHIs due to the use of customizable avatars that participants can use to either hide or highlight parts of their identities. It is critical to assess the sociodemographic factors that correlate with attitudes toward MMHIs in order to understand which populations may be particularly willing or unwilling to use MMHIs.

Mental Health Factors

Synchronous DMHIs may be preferred to face-to-face interventions for individuals experiencing common mental health disorders, such as anxiety (particularly social anxiety) and depression, due to reduced social interaction-related stress [19] and reduced stigma and embarrassment when the DMHI is anonymous [20]. MMHIs are synchronous and anonymous, which may make them particularly attractive to individuals with elevated levels of social anxiety or depression symptoms. Furthermore, negative attitudes toward mental help-seeking remain a barrier to the use of DMHIs [20]. The unique features of MMHIs, such as their ability to balance a sense of presence and anonymity [7], may prove attractive to those who would otherwise not seek treatment due to negative attitudes toward mental help-seeking.

Technology Factors

Attitudes toward technology appear to be generally related to attitudes toward DMHIs [21]. Since the metaverse and virtual worlds are historically computer based [22], attitudes toward computers specifically may be related to attitudes toward peer-supported MMHIs. Moreover, peer-supported MMHIs share strong mechanistic similarities with online multiplayer video games. Not only do such games facilitate anonymous communication and group social interaction, but most of the mechanics and navigation elements of MMHIs would be familiar to gamers, such as "avatars," "push to talk" buttons, and immersion in a virtual world. Online video game use may, therefore, be a pertinent factor in attitudes toward peer-supported MMHIs.

Study Aims

The aim of this study was to assess factors that may predict general interest in MMHIs, as well as preference for MMHIs versus face-to-face interventions. To accomplish this objective, we conducted a web-based survey in a diverse sample from the general population to assess sociodemographic, mental health, and technology factors that could be associated with attitudes toward peer-supported MMHIs.

Methods

Study Design

This study involved a mixed methods design with data gathered from an open, voluntary, web-based survey. The online survey included a variety of quantitative self-report measures of attitudes toward different interventions, sociodemographic factors, mental health factors, and technology factors. The survey also included open-ended questions used to gather qualitative data on participants' reasons for their attitudes toward intervention types. We chose this study design because it is feasible for participants and can easily reach a large, diverse sample. Reporting followed the Checklist for Reporting Results of Internet E-Surveys (CHERRIES; see [Multimedia Appendix 1](#) for the checklist) [23].

Recruitment

Inclusion criteria for the study were (1) ability and willingness to provide informed consent and (2) age of 18 years or above. There were no exclusion criteria for this study. Participants meeting these criteria were recruited to participate in the survey using word-of-mouth, flyers distributed around our university campus, social media posts on the networks Reddit and X (formerly Twitter), and Prolific (a web-based recruitment platform) [24]. Recruitment occurred from April to July 2023. Initial contacts for recruitment occurred online via the social media posts, except for a few individuals who received a paper flyer on our university campus. For social media, a single post was made to each social media site with information about the study and a direct link to complete the study consent form and survey. The survey was posted 4 times on Prolific to target different individuals identifying as part of various racial/ethnic groups (using Prolific's available demographic-screening options).

We calculated our anticipated sample size using the recommendation of at least 10 events per variable in a logistic regression [25-27]. This recommendation helps avoid overfitting and biased estimates. We originally planned to include 19 predictors in our model, which resulted in an estimated sample size of 380 participants. However, some of these predictors were removed after preliminary examination of the data (eg, presence of highly related predictors). This recommendation is only a minimum, and a higher number of events per variable is almost always preferable [28]. Due to the unexpected strong success of our recruitment strategies, recruitment continued until we could no longer fund recruitment.

Procedures

Participants who accessed the study link via the online posts or by scanning the QR code on paper flyers were redirected to a University of Southern California (USC) Qualtrics page and presented with an information sheet for the study. The information sheet included the estimated study length of 9 minutes and a data storage policy for the collection of anonymous data. Participants were then asked to provide consent. Those who consented to participate in the study were asked to complete a series of self-report measures assessing sociodemographic, mental health, and technology factors.

Participants were then asked to watch a short video clip showing an example of a mental health intervention taking place in the metaverse (Innerworld, developed by Innerworld, Inc [7], was used as an example of a peer-supported MMHI). Lastly, participants completed measures of their attitudes toward MMHIs. Prolific participants were compensated with US \$2 for completing the survey, while all other participants were provided with the chance to be selected for a US \$100 gift card raffle.

The survey was hosted on Qualtrics with a black-and-white color scheme and official USC branding. We implemented IP address monitoring and browser cookie measures in Qualtrics in order to prevent the same user from completing the survey multiple times during the duration of the study. The survey's usability and functionality were assessed by investigators and close colleagues prior to data collection. An attention check question was included, which participants had to answer correctly to proceed with the survey. The survey used adaptive questioning to reduce participant burden, but we did not randomize the order of items or question blocks for individual participants. Respondents could not review previous answers. Completeness was reported automatically by Qualtrics, but survey responses were also reviewed manually. Fraudulent responses were removed after a thorough examination, including checking for impossible or exceptionally fast time stamps (at least 3 SDs below the mean duration), abnormally low clicks counted, nonsensical or artificial intelligence (AI)-generated open-ended responses, and "straight-lined" answers.

Ethical Considerations

This study was approved by the USC's Institutional Review Board at the exempt level (approval number: UP-23-00491). Data were anonymized and contained no identifying information.

Measures

Sociodemographic Factors

Participants were asked to provide their ethnicity/race, gender identity, and age. Participants were also asked whether they had access to the internet or a smartphone or both. Consistent with prior work on ethnic identity centrality [29-31], we asked participants to indicate their level of ethnic identity centrality ("How important is your racial or ethnic background to your identity as a whole?") on a 5-point scale ranging from 1 (not at all important) to 5 (extremely important).

Mental Health Factors

Mental Help-Seeking Attitudes

The Mental Help Seeking Attitudes Scale (MHSAS), a 9-item self-report measure, was used to evaluate participant attitudes toward seeking help from a mental health professional. The MHSAS is a validated [32] bipolar scale with 7 response options to each item anchored on either end by dichotomous adjectives (eg, good, bad). A mean total score is computed, with higher scores indicating more positive attitudes toward seeking mental help.

Level of Depression Symptoms

Depression symptoms were measured using the 8-item Patient Health Questionnaire (PHQ-8), a well-validated and reliable self-report measure of depression symptoms [33]. Each item is rated on a 0–3-point Likert scale, and a sum total score is computed, with higher scores indicating greater depression symptom severity. This variable was categorized according to severity categories set by the authors of this instrument: 0–4 indicating no symptoms, 5–9 indicating mild symptoms, 10–14 indicating moderate symptoms, 15–19 indicating moderately severe symptoms, and ≥ 20 indicating severe symptoms.

Level of Social Anxiety Symptoms

Social anxiety symptoms were measured using the Mini-Social Phobia Inventory (Mini-SPIN) [34]. The Mini-SPIN is a validated [35–37] 3-item self-report screening tool that asks participants to rate, in the past week, how much (ranging from 0 for *not at all* to 4 for *extremely*) they have been bothered by problems related to social anxiety. A sum total score is computed, with higher scores indicating greater social anxiety symptom severity. This variable was dichotomized based on suggestions from the authors of this instrument, with a score of 6 or greater indicating the presence of a clinical level of symptom severity.

Technology Factors

Computer Attitudes

To evaluate attitudes toward using computers, we adapted the Computer Attitudes subscale of the well-validated Computer Aversion, Attitudes, and Familiarity Index (CAAFI) [38–40]. The subscale consists of 9 items asking participants to select the response, ranging from –3 (absolutely false) to 3 (absolutely true), that best describes how true or false a statement is to them. A sum total score is computed, with higher scores indicating more positive attitudes toward using computers. We removed 3 items that were outdated with regard to the cultural mass usage of computers and email in the recent decade (“I use a computer input device every day,” “I use email every day,” and “Email is an easy way to communicate with people.”).

Video Game/Internet Use Habits

Similarly to previous research assessing internet habits [41,42], participants self-reported how often (ranging from 1 for *never* to 5 for *very often*) they engaged in specific activities while connected to the internet (eg, “playing online video games”).

Virtual Reality Experience

Consistent with prior work [43,44], we used a single item with 4 response options ranging from 1 (no experience) to 4 (a lot of experience) to assess participants’ previous experience with virtual reality (VR) technology.

Outcome Variables

General Interest in Peer-Supported MMHIs

We adapted a single-item measure commonly used across disciplines to assess overall willingness to use a peer-supported MMHI [45,46]. Participants were asked how willing they would be to use a peer-supported MMHI if money was not a concern,

with response options ranging from 1 (not at all willing) to 5 (extremely willing).

Preference for Peer-Supported MMHIs Versus Face-to-Face Interventions

A single item asked whether participants would prefer to use a peer-supported MMHI or a face-to-face peer-supported mental health intervention. A 5-point scale was used such that participants could either indicate no preference, a mild preference (somewhat prefer), or a strong preference (definitely prefer) for either MMHIs or face-to-face interventions.

Qualitative Variables

After participants were asked whether they would prefer to use a peer-supported MMHI or a face-to-face peer-supported mental health intervention, an open-ended question asked their reasoning behind their preference. At the end of the survey, another open-ended question asked whether there was anything else the participants wanted to share with the research team (see [Multimedia Appendix 2](#) for a copy of each investigator-devised scale and items used for this study).

Analytic Strategy

Quantitative data were analyzed using R version 4.3.1 [47]. In instances of missing item-level data, we prorated scores by averaging the available items. Before proration, 62 (11.4%) participant responses had some level of missingness across measures. After proration, 40 (7.3%) participant responses still contained some level of missingness across measures.

Quantitative Analyses

To examine predictors of interest in MMHIs, we conducted ordinal logistic regression, designed for modeling an ordinal dependent variable [48], in a 2-step approach. In the first stage, we ran a comprehensive model of the complete list of 13 predictors: Hispanic ethnicity, the male gender, age, income, ethnic identity centrality, internet access, smartphone access, mental help-seeking attitudes, the level of depression symptoms, the level of social anxiety symptoms, computer attitudes, self-reported video game use, and experience with VR. In the second stage, we evaluated a parsimonious model that retained the predictors that were significant in the comprehensive model at $P < .10$, similar to the procedures used previously to examine predictors of response variables in digital interventions [49,50].

Given the bimodal distribution of preference for MMHIs versus face-to-face interventions responses, we dichotomized this outcome variable. To examine the predictors of MMHI versus face-to-face intervention preference, we conducted binary logistic regression using the same 2-stage approach described earlier.

To ensure the validity of the modeling approaches, we checked the assumptions of each comprehensive and parsimonious model. For ordinal logistic regression, we visually assessed the distribution of responses in our outcome variable (ie, interest in MMHIs) and noticed that responses indicating little to no interest (scores of 1 and 2) were highly associated with each other and responses indicating moderate-to-strong interest (scores of 4 and 5) were highly associated with each other. Although interest in MMHIs was relatively normally distributed,

this raised concern for the validity of the proportional odds assumption in this data, which posits that the relationship (and, therefore, the odds ratio [OR] of coefficients) between each pair of outcome groups is the same [48]. As such, we collapsed the variable for interest in MMHIs into 3 categories: low interest (score of 1 or 2), neutral (score of 3), and high interest (score of 4 or 5). We checked for violations of the proportional odds assumption in the ordinal logistic model using the Brant test. For binary logistic regression, we visually checked for violations of the logit-linearity assumption between the outcome variable (ie, intervention preference) and continuous predictors. We assessed Cook's distance and studentized residual plots for each comprehensive and parsimonious binary logistic regression to detect potential outliers. Five outliers were removed from the comprehensive binary logistic regression model. Lastly, we checked for multicollinearity in both parsimonious models, with a variance inflation factor of 4 or greater indicating high multicollinearity [51].

Results of a Wilcoxon rank sum test showed that Prolific participants reported a significantly lower mean MMHI interest compared to the non-Prolific sample ($W=27258$, $P=.04$). Therefore, we included *recruitment method* as a covariate in our model examining predictors of MMHI interest, which did not alter the direction or significance of results. We did not find

a significant difference in MMHI versus face-to-face intervention preference with respect to recruitment method.

Qualitative Analyses of Open-Ended Responses

We conducted an inductive content analysis [52] on open-ended responses explaining participant preference for MMHIs versus face-to-face interventions. Analysis followed all 8 guidelines set out by Cofie et al [53] for maintaining reflexivity and reliability using a qualitative-based measure of intercoder reliability (see [Multimedia Appendix 3](#) for the checklist). Coding was performed using ATLAS.ti version 23.2.3.27778 for Windows [54]. First, authors FNR and RAB conducted an initial review of the data and generated a code framework. Second, all comments were coded by FNR and RAB, who subsequently discussed code groups and definitions and addressed points of contention. This step was repeated 3 times. The analytic process was recorded in research diaries, and no outstanding disagreements were observed after the discussions.

Results

Sample Characteristics

A total of 545 participants completed this study. The median survey completion duration was 8.9 minutes. A full sociodemographic breakdown of the sample assessed in this study is presented in [Table 1](#).

Table 1. Characteristics of participants (N=545) at baseline.

| Baseline characteristics | Values |
|---|---------------|
| Sociodemographic factors | |
| Hispanic ethnicity, n (%) | 161 (29.6) |
| Age (years), mean (SD) | 34.69 (12.75) |
| Ethnic identity centrality, mean (SD) | 3.04 (1.28) |
| Access to the internet, n (%) | 473 (86.8) |
| Access to a smartphone, n (%) | 490 (89.9) |
| Gender, n (%) | |
| Male (reference) | 261 (47.9) |
| Female | 265 (48.6) |
| Genderqueer | 2 (0.4) |
| Nonbinary/nonconforming | 14 (2.6) |
| Unknown | 3 (0.6) |
| Mental health factors, mean (SD) | |
| Mental help-seeking attitudes | 5.58 (1.19) |
| Depression symptom severity, n (%) | |
| None | 234 (42.9) |
| Mild | 160 (29.4) |
| Moderate | 92 (16.9) |
| Moderately severe | 33 (6.1) |
| Severe | 22 (4.0) |
| Clinical level of social anxiety symptoms | 184 (33.8) |
| Technology factors, mean (SD) | |
| Computer attitudes | 13.43 (5.94) |
| Online video game use | 3.14 (1.34) |
| VR ^a experience | 2.11 (0.92) |

^aVR: virtual reality.

Primary Analyses

General Interest in MMHIs

Regarding general interest in MMHIs, 192 (36.9%) of 520 participants reported low interest, 144 (27.7%) participants reported neutral interest, and 184 (35.4%) reported high interest.

In the parsimonious model, older age, higher ethnic identity centrality, lack of internet access, more positive mental help-seeking attitudes, more online video game use, and more VR experience were associated with greater interest in MMHIs. Results of this parsimonious ordinal logistic model are presented in [Table 2](#) (see [Multimedia Appendix 4](#) for results of the comprehensive ordinal model).

Table 2. Predictors of general interest in peer-supported MMHIs^a in the parsimonious ordinal logistic regression model and predictors of preference for peer-supported metaverse versus face-to-face interventions in the parsimonious binary logistic regression model.

| Predictors | Ordinal model | | | Binary model | | |
|--|--------------------------|-------|---------|--------------------|------|---------|
| | OR ^b (95% CI) | SE | P value | OR (95% CI) | SE | P value |
| Hispanic | — ^c | — | — | 1.81 (1.13-2.90) | 0.24 | .01 |
| Male gender | — | — | — | 0.43 (0.27-0.68) | 0.23 | <.001 |
| Age | 1.03 (1.02-1.05) | 0.007 | <.001 | 1.04 (1.02-1.05) | 0.01 | <.001 |
| Ethnic identity centrality | 1.44 (1.25-1.66) | 0.07 | <.001 | 1.28 (1.09-1.51) | 0.08 | .003 |
| Internet access | 0.50 (0.30-0.84) | 0.26 | .01 | 0.12 (0.02-0.40) | 0.69 | .002 |
| Smartphone access | — | — | — | 10.46 (2.87-50.71) | 0.71 | <.001 |
| Mental help-seeking attitudes | 1.22 (1.06-1.42) | 0.08 | .008 | 0.76 (0.62-0.92) | 0.10 | .005 |
| Depression symptoms^d | | | | | | |
| Mild | — | — | — | 0.85 (0.51- 1.42) | 0.26 | .54 |
| Moderate | — | — | — | 0.60 (0.32- 1.12) | 0.32 | .11 |
| Moderately severe | — | — | — | 0.20 (0.07- 0.51) | 0.49 | .001 |
| Severe | — | — | — | 0.26 (0.08- 0.79) | 0.58 | .02 |
| Computer attitudes | — | — | — | 1.05 (1.01-1.10) | 0.02 | .02 |
| Video game use | 1.26 (1.09-1.44) | 0.07 | .001 | 1.25 (1.05-1.48) | 0.09 | .01 |
| VR ^e experience | 1.55 (1.28-1.90) | 0.10 | <.001 | — | — | — |

^aMMHI: metaverse mental health intervention.

^bOR: odds ratio.

^cNot applicable.

^d“No depression” was used as the reference group for all depression symptom variables.

^eVR: virtual reality.

Preference for MMHIS Versus Face-to-Face Interventions

A total of 233 (42.8%) participants reported preference for MMHIs over face-to-face interventions, 223 (40.9%) participants reported preference for face-to-face interventions over MMHIs, and 64 (11.7%) participants indicated no preference. In the parsimonious model, Hispanic ethnicity, older age, higher ethnic identity centrality, smartphone access, more positive computer attitudes, and higher self-reported video game use were associated with greater odds of preference for MMHIs (versus face-to-face interventions). The male gender, internet access, more positive mental help-seeking attitudes, and higher levels of depression symptoms were associated with lower odds of preference for MMHIs (versus face-to-face interventions). Results of this parsimonious binary logistic model are presented in [Table 2](#) (see [Multimedia Appendix 4](#) for results of the comprehensive binary logistic model).

Qualitative Analyses of Open-Ended Responses

We analyzed 483 comments elaborating on participant preference for peer-supported MMHIs versus peer-supported face-to-face mental health interventions. Analysis revealed 14 codes describing reasons for participants' indicated preference: anonymity; social aversion; anxiety; comfort; ease of use and accessibility; ecological validity of social interaction; ecological validity of intervention; impersonal quality; aversion/distrust

toward technology, the metaverse, or others in the metaverse; mental health attitudes; novelty/experience; privacy; immersion/engagement; and miscellaneous. An overview of the codes and their definitions by preference, as well as representative quotes for each, is presented in [Multimedia Appendix 5](#).

Reasons related to anonymity or benefits of anonymity, such as reduced bias from others (133/483, 27.5%); an aversion to social, particularly face-to-face, interaction (38/483, 7.9%); greater ease of use and accessibility in the preferred intervention (35/483, 7.2%); anxiety, particularly social anxiety (28/483, 5.8%); and greater general comfort/greater comfort with negative feelings in the preferred intervention (26/483, 5.4%) tended to be endorsed by participants who indicated preference for MMHIs. Reasons related to poor ecological validity of social interaction in the nonpreferred intervention, such as lack of body language (99/483, 20.5%); poor ecological validity of the nonpreferred intervention itself, such as unrealistic graphics (75/483, 15.5%); aversion to the metaverse or distrust of affiliated companies or others in the metaverse social space (42/483, 8.7%); an “impersonal quality” of the nonpreferred intervention, often tied to perceived insincerity and overly distant social relations (31/483, 6.4%); and anticipated difficulty remaining engaged in the nonpreferred intervention (11/483, 2.3%) tended to be endorsed by respondents who preferred face-to-face interventions. Reasons related to mental health

attitudes (28/483, 5.8%), privacy (19/483, 3.9%), and miscellaneous points (46/483, 9.5%) were endorsed approximately equally across preferences. The novelty of MMHIs/a lack of experience with MMHIs or mental health interventions (21/483, 4.3%) was most cited by those who expressed no preference.

Discussion

Principal Findings

Our quantitative analysis revealed that older age, higher ethnic identity centrality, lack of internet access, more positive mental help-seeking attitudes, more online video game use, and more VR experience were associated with greater odds of more interest in MMHIs. Hispanic ethnicity, older age, higher ethnic identity centrality, smartphone access, more positive computer attitudes, and higher self-reported video game use were associated with greater odds of preference for MMHIs (versus face-to-face interventions). The male gender, internet access, more positive mental help-seeking attitudes, and higher levels of depression symptoms were associated with lower odds of preference for MMHIs (versus face-to-face interventions). Our qualitative analysis revealed 14 themes related to participants' reasons for why they prefer MMHIs versus face-to-face interventions. Among respondents who preferred MMHIs, reasons cited touched upon themes related to anonymity, social aversion, ease of use and accessibility, anxiety, and comfort. Among those who preferred face-to-face interventions, reasons touched upon ecological validity of social interaction, ecological validity of intervention, aversion/distrust toward technology, impersonal quality, and immersion/engagement. Mental health attitudes, privacy, and miscellaneous reasons were endorsed equally between preferences, and novelty was most cited by those who expressed no preference.

Comparison to Prior Work

Regarding sociodemographic variables, our findings suggest that older adults may be more likely to report higher interest in MMHIs and find MMHIs more attractive than face-to-face interventions, assuaging potential concerns about the accessibility of MMHIs to these individuals [55]. Furthermore, internet access was found to be associated with a lower likelihood of reporting higher interest in MMHIs and of preferring MMHIs to face-to-face interventions. It may be that individuals without internet access are less familiar with the metaverse or online social environments and may find the idea novel and more appealing. Smartphone access was associated with greater odds of preference for MMHIs over face-to-face interventions. Smartphones are often cheaper and more easily accessed than a stable home internet connection, suggesting that those without smartphone access may be particularly averse to or unfamiliar with MMHIs or their type, such as DMHIs. Greater ethnic identity centrality also appeared to be associated with a greater likelihood of reporting higher interest in MMHIs, as well as a greater likelihood of preference for MMHIs versus face-to-face interventions. Qualitative responses from metaverse preferers often seemed to reflect an expectation of reduced bias and discrimination for their race or appearance in MMHIs as opposed to face-to-face interventions, possibly due to lower

salience of identity in the metaverse. Hispanic ethnicity was associated with greater odds of preferring MMHIs as opposed to face-to-face interventions but not associated with interest in MMHIs. It is possible that Hispanics are more likely to prefer MMHIs to face-to-face interventions but not more likely to be interested in using a mental health intervention than non-Hispanics.

Regarding our examination of mental health factors, the greater likelihood of those with more positive attitudes toward mental help-seeking to be more interested in MMHIs might suggest that those who view mental help-seeking more positively may be more likely to view mental health interventions more positively in general. However, the association between more negative attitudes toward mental help-seeking and greater preference for MMHIs versus face-to-face interventions may indicate potential for peer-supported MMHIs to reach out to individuals who otherwise view mental health interventions unfavorably. This was echoed in the qualitative data by respondents who felt that discussing their mental health issues would be easier or less embarrassing in an MMHI than in a face-to-face intervention. However, we also found that participants with moderately severe or severe depression symptoms had greater odds of preferring face-to-face interventions to MMHIs than those with no depression symptoms. This may suggest that peer-supported MMHIs (which are low intensity) may not currently be a more attractive mental health intervention option than face-to-face intervention options for those struggling with more severe depression. Finally, we did not find a relationship between clinical levels of social anxiety symptoms and attitudes toward MMHIs, but our qualitative analysis did reveal a theme of anxiety, wherein comments tended to suggest that the respondents anticipated feeling less nervous in an MMHI than in a face-to-face intervention, often due to their anonymity. The findings regarding the relationship between anxiety and attitudes toward peer-supported MMHIs necessitate further study to elucidate the relationships between these factors.

Finally, the positive association between all 3 technology factors and at least 1 of the outcome variables, combined with the importance of the perceived "realness" of MMHIs and social interactions within them, as revealed in the qualitative analysis, suggests that the digital platform and technological novelty of MMHIs may factor into participant attitudes toward these interventions. However, only online video game use was significant in both ordinal and binary logistic regression models, possibly due to greater conceptual overlap of the videogame-like nature of current MMHIs. The promotion of MMHIs to technologically inclined individuals should be encouraged to connect help-seeking individuals with mental health services they are likely to be interested in. However, our findings also indicate that low ratings on certain technology factors, such as experience with VR, could serve as a barrier to willingness to use an MMHI. Furthermore, given the inconsistent associations between the technological factors measured and our dependent variables, there are likely other technological factors we did not assess that are associated with attitudes toward MMHIs. Attempting to replicate these findings by investigating lack of experience with technology and other technology factors as

potential barriers to seeking MMHIs should be a direction of future research.

Strengths and Limitations

To the best of our knowledge, this is the first study to identify factors associated with general interest in peer-supported MMHIs, as well as preference for peer-supported MMHIs versus peer-supported face-to-face mental health interventions. Our mixed methods approach was able to capture complementary quantitative and qualitative data that can offer a more comprehensive assessment (than either approach alone) of factors influencing participants' attitudes toward MMHIs. However, we noted some limitations of this study. First, we examined a limited number of factors that could influence attitudes toward peer-supported MMHIs. We tried to mitigate this limitation by conducting a thorough review of the literature to identify candidate predictors across a variety of domains (sociodemographic, mental health, and technology). Nonetheless, future work would benefit from investigating other factors. Second, we examined predictive factors of attitudes toward peer-supported MMHIs in a general sample. Assessing these factors in a clinical sample may return different findings that help explain the similarly low level of interest in MMHIs as with face-to-face interventions for individuals with clinical depression or social anxiety. However, we did collect depression and social anxiety symptom data and observed that our sample had representation in each of the symptom severity categories assessed on the measures. Third, it was not always clear what factors an individual participant considered when reporting attitudes. A participant may or may not have considered the metaverse setting, the peer support element, the mental health emphasis, or a number of other factors. Although we sought to contextualize reported preferences using qualitative data, more work is needed to deepen the field's understanding of the most

salient aspects of peer-supported MMHIs that attract or deter participants.

Future Directions

Future work could benefit from assessing the role of other attitudes (eg, attitudes toward companies hosting MMHIs) or technology factors that may be more directly relevant to MMHI use (eg, confidence/competence with technology, number of hours using related technology). We also encourage future research on the acceptability and feasibility of MMHIs with diverse samples to ensure the validity and generalizability of these findings.

Conclusion

This study assessed attitudes toward peer-supported mental health interventions delivered via the metaverse. By identifying sociodemographic, mental health, and technology factors associated with attitudes toward peer-supported MMHIs, our findings represent the first venture into identifying the individuals and populations who may be especially willing to use peer-supported MMHIs or for whom MMHIs may be more attractive than face-to-face interventions (eg, older adults, those with more negative mental help-seeking attitudes). The results of this study serve to inform the future development and outreach plans of MMHIs by identifying populations that may be particularly likely or unlikely to be interested in MMHIs. If replicated, this information could potentially be used to optimize treatment outreach to interested populations, especially those who may not seek mental help otherwise (eg, by increasing the quantity and promotion of technical support, including help documents, to encourage MMHI use by older adults), or to change aspects of MMHIs to better appeal to disinterested populations. Future work is encouraged to confirm the salience of the factors identified in this study to attitudes toward MMHIs and to assess predictive factors of outcomes when using an MMHI.

Data Availability

The data sets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Conceptualization, methodology, project administration, and writing—original draft were managed by FNR and IDE; data curation, formal analysis, and investigation by FNR; supervision by IDE; and writing—review and editing by FNR, RAB, and IDE.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Checklist for Reporting Results of Internet E-Surveys (CHERRIES).

[\[DOCX File, 20 KB - xr_v1i1e57990_app1.docx\]](#)

Multimedia Appendix 2

Investigator-devised scales and items used for this study.

[\[DOCX File, 17 KB - xr_v1i1e57990_app2.docx\]](#)

Multimedia Appendix 3

Checklist of recommendations for reporting intercoder reliability in qualitative research from Cofie et al [53].

[[DOCX File , 17 KB - xr_v1i1e57990_app3.docx](#)]

Multimedia Appendix 4

Results of comprehensive logistic models.

[[DOCX File , 23 KB - xr_v1i1e57990_app4.docx](#)]

Multimedia Appendix 5

Themes from qualitative analysis of open-ended responses.

[[DOCX File , 18 KB - xr_v1i1e57990_app5.docx](#)]

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Abbreviations

- DMHI:** digital mental health intervention
- MHSAS:** Mental Help Seeking Attitudes Scale
- Mini-SPIN:** Mini-Social Phobia Inventory
- MMHI:** metaverse mental health intervention
- OR:** odds ratio
- USC:** University of Southern California
- VR:** virtual reality

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Original Paper

Experience of Youths and Older People With Virtual Reality Games for Cognitive Assessment: Inductive Thematic Analysis and Insights for Key Stakeholders

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Abstract

Background: Virtual reality (VR)-based goal-oriented games for cognitive assessment are rapidly emerging and progressively being used in neuropsychological settings. These games have been validated quantitatively, but minimal qualitative insights from users currently exist. Such insights on user experience are essential to answering critical questions linked to the games' large-scale usability, adoption in hospital settings, and game design refinement. Current qualitative studies on these games have used general questionnaires or web-based reviews to answer these questions, but direct observation from primary settings is missing. We believe that direct observation of participants playing these games and subsequent interaction with them is critical to developing a more objective, clear, and unbiased view of the games' efficacy, usability, and acceptability.

Objective: In this study, we aimed to extract constructive and relevant insights directly from the participants who played VR-based goal-oriented games. We used these insights to answer vital questions linked to the practical utility of VR-based cognitive assessment. On the basis of these results, we also aimed to provide actionable insights to key stakeholders in the field, such as researchers, game developers, business personnel, and neuropsychology and allied professionals.

Methods: Interview data from 82 younger (aged 18-28 years) and 42 older adult (aged >60 years) participants were used. The interview data were obtained from the 2 pilot studies we conducted on VR games for cognitive assessment. Inductive thematic analysis was conducted on the interview data, and later, the findings were carefully interpreted to develop implications for the key stakeholders.

Results: We identified 5 themes: ergonomic issues, learning and training, postgame effects, game feedback, and system purpose. Regarding hardware, headset weight, adjustment straps, and controllers need to be improved to promote easy use of the device. Regarding software, graphics quality, immersion experience, and game mechanics are the primary deciding factors for a positive user experience. The younger group prioritized purpose and utility for long-term use, whereas the older participants cherished the entertainment aspect. Researchers and game developers must conceptualize and develop games that can provide maximum insights into real-world abilities. Manufacturing businesses need to improve the headset and accessories to make them more user-friendly. Finally, neuropsychology and allied practitioners must identify strategies to engage and train the participants to try VR-based cognitive assessment games.

Conclusions: VR-based games for cognitive assessment are promising tools to improve the current practices of neuropsychological evaluations; however, a few changes are required to make the overall user experience enjoyable, purposeful, and sustainable. In addition, all the key stakeholders need to focus on meaning and purpose over the hype of VR and are advised to work in synergy.

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KEYWORDS

virtual reality; cognitive assessment games; inductive thematic analysis; youth; older adult; cognitive; cognitive assessment; virtual reality games; game; games; thematic analysis; neurological; utility; cognitive assessment tools; game based; cognitive games

Introduction

Background

Games for cognitive assessment have become very popular [1-6]. This development is motivated by the urgency for early detection of cognitive deficits such as dementia, which do not have a cure [7]. Moreover, traditional methods for cognitive assessment provide limited assistance for early detection of cognitive decline and fail to instruct about the real-world cognitive abilities of people [8-10]. In this context, goal-oriented games can serve as novel tools to address the gaps associated with traditional neuropsychological assessments [11].

Games for cognitive assessment can be either immersive or nonimmersive. The nonimmersive games are played on mobile-, tablet-, or computer-based platforms, whereas immersive games use virtual reality (VR) devices, usually a head-mounted display (HMD) and handheld controllers. Games in both the immersive and nonimmersive environments are effective for evaluating and assessing specific cognitive abilities such as memory, language, spatial abilities, and executive functioning and assist in stroke [12-15] and traumatic brain injury rehabilitation [16,17].

Of the 2 types of games, immersive games have generated a lot of excitement and enthusiasm among researchers, clinical personnel, and commercial enterprises [18]. The VR framework can create interactive and immersive 3D environments, which can simulate the real world. This simulation-based realism of VR environments is conducive to ecologically valid cognitive assessment [19-21]. In fact, VR games can assess the ability to carry out activities of daily living [22], detect visuospatial deficits [23-25], and assess cognition in general [26]. In addition to cognitive assessment, VR games are used for rehabilitation of executive functioning [27,28], memory impairment control [29-31], language improvement [32,33], and motor rehabilitation [34].

Clearly, VR games are useful for cognitive assessment and rehabilitation. Research studies have validated this usefulness through statistical and correlational analyses [22-24,35], and systematic reviews and meta-analyses also confirm the advantages [36-38]. However, quantitative validation is insufficient to deduce the acceptability and adoption of these tools in real-world neurological or medical settings. In fact, according to a qualitative study on 3 focus groups and 60 one-to-one interviews, the functional aspect of technology has little impact on its adoption [39].

Skewed focus on the quantitative validation of VR games exaggerates their functional aspects while completely ignoring the emotional, social, and epistemic aspects that are crucial to their adoption [40,41]. For a fuller validation of these games, it is essential to know users' attitudes toward them; the complexity they face during use; and the extent of compatibility

between the technology and their needs, values, and experiences. These factors can inform the perceived usefulness and ease of use of such VR games, ultimately indicating the likelihood of their adoption in the real world. The US Food and Drug Administration also advocates for qualitative evidence from key stakeholders on VR tools' relevance and significance [42].

While numerous reviews have established the impact of VR games for measuring and improving cognitive abilities such as executive functioning, spatial reasoning, memory, language, and attention, as well as activities of daily living [43], we still know very little about how users actually feel about these games. Therefore, to obtain perspectives beyond functionality in the context of VR games for cognitive assessment, studies that review and inform user experience and feedback are vital. Existing reviews in this context focus on web-based data [44-46], lack age-specific investigation [44-46], or simply focus on game design elements [47,48]. This lack of focus and direction from the user point of view is detrimental and fruitless to inform the acceptance and adoption of these tools in the real world.

In this context, we undertook this thematic analysis and distilled feedback on VR games for cognitive assessment obtained from 2 cohorts: 93 younger (aged 18-28 years) and 53 older (aged >60 years) participants. Data were obtained from 2 field trials conducted by us. The younger cohort was recruited from the Birla Institute of Technology and Science (BITS) Pilani K. K. Birla Goa Campus, and the older cohort was recruited from the Annasawmy Mudaliar General Hospital, Bangalore, India. All participants were cognitively healthy except for 2 in the older cohort who reported mild cognitive impairment.

Using thematic analysis, we extracted practical, applied, and insightful themes that inform about the strengths, challenges, and limitations of the VR games for cognitive assessment. We discussed the obtained themes and substantiated them through user comments. In a separate section for stakeholders, we discussed the implication of the findings for researchers, game developers, businesses, and medical settings. Our work is relevant to anyone who works at the forefront of using and developing VR games for cognitive assessment and rehabilitation.

In the next section, we present and discuss review studies on immersive and nonimmersive games for cognitive assessment. Later, we briefly describe the methodology used. Finally, the results are presented and discussed, followed by conclusions.

Literature Review

In this section, we briefly mention studies that quantitatively validate VR-based cognitive assessment games and acknowledge their importance for the translation of these games into the real world. Importantly, we also contrast the significance of qualitative studies on VR-based cognitive assessment games compared to these quantitative validation studies and develop

a case for the former's importance for real-world translation. Finally, we discuss previous qualitative studies on VR games and point out their limitations and contributions and, against this context, justify the significance of our work.

A meta-analysis of 18 studies found that healthy controls scored higher in games for executive functions, visuospatial abilities, and memory as compared to those with cognitive impairment [36]. Accordingly, the authors concluded that VR-based measures for cognitive processes are sensitive in detecting cognitive impairment. A different study established the criterion validity of the VR games for cognitive assessment using 5 factors of personality and convergent validity using scores of computer-based assessments [35], further validating the efficacy of VR-based cognitive assessment. However, the authors also pointed out the need to evaluate these games for their difficulty, adaption, autonomy, and control.

A systematic review of digital games for attention found that quantitative validation of game scores was primarily done against the traditional psychometric counterparts and clinical diagnosis [49] but the enjoyment properties of the games were rarely evaluated. In addition, a meta-analysis and systematic analysis that found VR games to be effective for rehabilitation of older adult patients after stroke remarked the importance of investigating game characteristics that drive positive changes in rehabilitation [37]. In the aforementioned studies, the authors sufficiently proved the validity of the VR games for cognitive assessment but also emphasized the need to examine the qualitative factors to obtain more clarity on the effectiveness and usability of these games. Clearly, there is a consensus among researchers on identifying and examining the factors associated with the wider adoption of these games. In fact, according to the theory of consumer research, knowledge of factors such as emotions, social value, and epistemic value is critical to sense user perception of a product's usefulness and adoption [40,41]. In this context, we discuss and critically analyze previous studies that inform our qualitative understanding of VR games.

A nonsystematic literature review on VR games for identification and rehabilitation of cognitive disorders reported nausea and disorientation among participants who played the games [50]. Although the authors described the games, the lack of specific insights into the game design and game elements precluded a deeper understanding of the causal factors for nausea and disorientation. Similarly, a narrative review of 29 papers on VR games summarized game designs used in VR game development [47]. However, we do not know how certain game designs are better or more effective than others for the usefulness and ease of use of VR games. On the other hand, a systematic review [48] found that score system and narrative context were the most popular game elements for neuropsychological assessment, training, and rehabilitation, but we do not know how the actual users feel about these popular game elements.

Each of these aforementioned reviews [47,48,50] is limited in its application to the real world as it is based on literature rather than direct user feedback. Although they provide a general understanding of game design, scores, game elements, and their aftereffects, reviews based on direct human experience and

feedback are preferable to inform the public-level acceptance and adoption of VR games for cognitive assessment. In fact, direct user opinions and feedback are crucial to ground the VR-based games for cognitive assessment and help separate practical utility from the VR hype [51-54]. To this end, we also discuss some studies that explore user feedback on VR games.

Analysis of 473 VR gamers' experience found that their use was primarily driven by enjoyment rather than usefulness [44]. Given that the sample comprised dedicated gamers, it is difficult to extrapolate these results to the general populace. Moreover, we do not know which types of games were played by these participants. Thus, even though the sample was large, its utility for reviewing the efficacy of VR games for cognitive assessment is precluded due to lack of information on the types of games played by the participants. Furthermore, the gamers were from different countries, and thus, cultural factors may be responsible for certain VR game preferences [55,56].

In a different study, web-based reviews of VR exergames sold in Steam, VIVEPORT, and Oculus were thematically analyzed, and it was found that realism, intuition, and skill enhancement were associated with positive user engagement, whereas a high number of bugs, poor graphics, and confusing control buttons were associated with user disengagement [45]. Similarly, a study on 1227 experienced VR gamers (6 months of experience) found that display quality, interactivity and service, enjoyment, and perceived control were indirectly linked to acceptance of and continuous intention to play the games [46].

The results of these 2 studies [45,46] provide a broad idea of qualitative aspects of VR games that are favorable and unfavorable for user acceptance, but because these studies are based on web-based reviews [45] and questionnaires [46], their impact is limited and lacks context required for real-world application and influence [52,53,57]. Consequently, it is difficult to discern from the aforementioned studies which features to continue with in VR game development, which to remove, and which to improve for cognitive assessment. To address this gap, it is vital to combine the findings of these reviews with direct feedback from participants in primary settings. Such direct feedback provides clearer information on user attitude toward the games, the challenges they face, and the perceived strengths of the game. Moreover, the opportunity to directly talk to the participants about their experience enriches the evidence base required to objectively establish the acceptance and adoption of VR games for cognitive assessment.

In summary, we observe that the existing evidence on validation of VR games for cognitive assessment is quantitative, lacks discussion and critical analysis of the context and content of the games, and is limited by lack of direct user feedback. Although existing quantitative evidence proves the functionality and potential of these games, it cannot be solely relied upon to indicate the acceptance and adoption of these games in real-world settings such as health centers for older people, old-age homes, neurological clinics, or even at home for individual assessment.

In this context, we present our thematic analysis, which is based on interviews conducted during 2 field trials on VR games for cognitive assessment undertaken by us. The games were

developed by us, and through these field trials, we obtained direct insights into the experience and feedback from youths (aged 18-28 years) and older participants (aged >60 years). The choice of a younger group was motivated by evidence of cognitive decline beginning in the third decade of life [58-72]. On the basis of the thematic analysis of the field trial data, we have richer insights into the user perception of VR games for cognitive assessment. We also present and discuss the implications of the findings for the key stakeholders in the field to foster real-world translation of the results, a practical goal that is missing in the aforementioned studies.

Methods

Overview

Our thematic analysis was based on the interview data we collected as part of our pilot on VR games among 82 younger participants (aged 18-29 years) and 42 older adult participants (aged ≥60 years). The youths were recruited from BITS Pilani K. K. Birla Goa Campus, and the older adults were recruited from the Annasawmy Mudaliar General Hospital, Bangalore, India.

In total, 2 VR games were piloted: a navigation game (Figure 1) and a hand-eye coordination game (Figure 2). The navigation game is an obstacle course game in which the participant has to wear the VR headset and use the handheld controllers to travel (walk and fly) through an animated virtual world course (land and sky), collect coins (rewards), identify turning points, and avoid obstacles to reach the final treasure (Figure 3). In the flying course, the participant uses controllers to fly and collect the coins in hoops suspended in the air.

In the hand-eye coordination game, the player is expected to hit blue cubes using a blue hammer (VR controller) and red cubes using a red hammer (Figure 2). The blue hammer is in the left hand of the player, and the red one is in the right hand.

A correct hit is registered when the red or blue cube is correctly hit by the red or blue hammer respectively in the direction specified on the incoming cube. Any other hit is incorrect. With every correct hit, the speed of the incoming cubes increases. Each participant played 3 trials of each VR game after playing a mini game that served as a tutorial for the actual game. An Oculus VR headset was used.

Both VR games were piloted in the younger group, but only the hand-eye coordination game was piloted in the older group due to the complex gameplay of the navigation game and the preliminary feedback of 2 older adults (aged >60 years). Before game administration, participants' basic level of proficiency with gaming, VR, and computers was obtained using a 5-point visual analog scale wherein 1 indicated the least experience and 5 indicated maximum experience. These data were important for contextual interpretation of game performance and feedback.

After game administration, feedback was obtained using 3 standard questionnaires: Virtual Reality Sickness Questionnaire [73], Virtual Reality Presence Questionnaire [74], and the System Usability Scale [75]. On the basis of the feedback from these 3 questionnaires, each participant was interviewed to obtain clarity on the context that guided their responses to the questionnaires. These interview data were used for the thematic analysis. The entire process took 1 hour for each participant.

Each individual comment was first coded to summarize its overall idea. Later, codes that were semantically similar were grouped together to form a theme. Themes were identified and later reviewed. Themes were categorized and named to reflect the codes they encompassed. In addition to the thematic analysis, we summarized the scores on the 3 questionnaires for each group. A statistical comparison between the groups was not possible because the older cohort did not play the navigation game. Finally, in a separate section, we discuss the implications of the findings for the key stakeholders in the field.

Figure 1. Navigation game sky view. The brown path and course can be seen, and the red and blue game elements indicate obstacles. The orange-colored hoops in the sky with suspended coins inside them illustrate the flying segment of the game.



Figure 2. Hand-eye coordination game first-person view. In total, 2 hammers can be seen (red and blue colored); each incoming cube has a direction arrow attached to it that indicates the desired motion of the hammer.

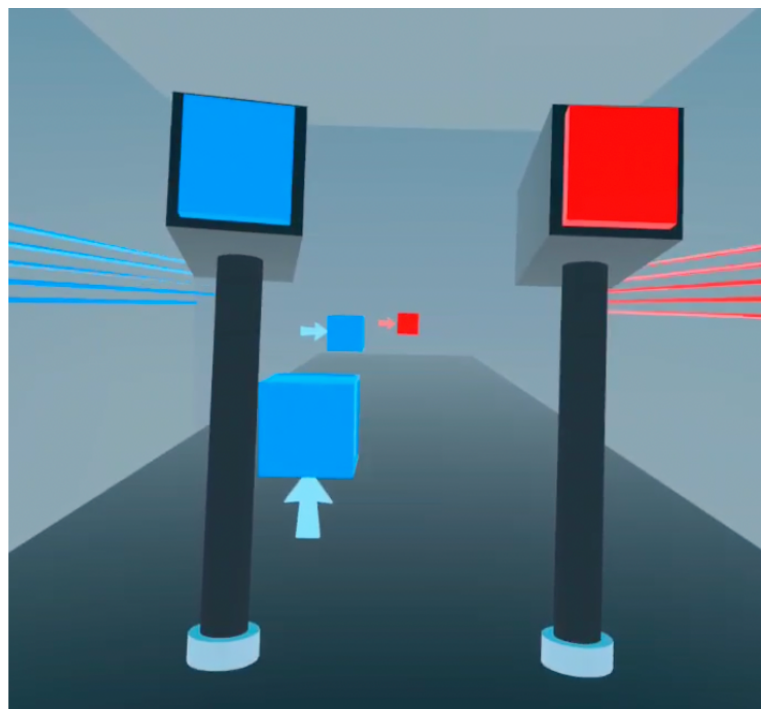
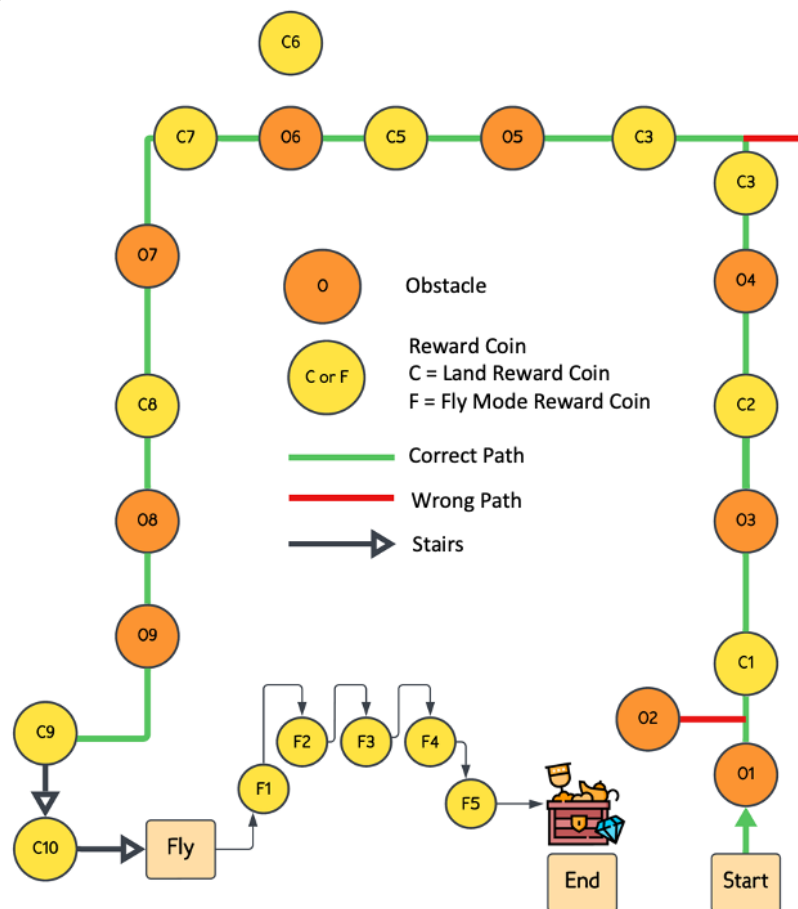


Figure 3. An abstraction of the virtual reality–based navigation game showing the obstacles, rewards (on the land and flying section), correct and incorrect paths, and the flying section.



Ethical Considerations

Written informed consent to take part in this study was provided by the participants. The procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975 as revised in 2008. All procedures involving human patients were approved by the Human Ethics Committee of BITS Pilani Goa Campus (reference HEC/BITS Goa/2023-2026). Ethics approval was also obtained from Annasawmy Mudaliar General Hospital separately for the recruitment and assessment of older adults.

Results

Overview

A total of 82 younger (mean age 20, SD 2.09 y; median age 20 y; $n=67$, 82% male) and 42 older (mean age 71, SD 6.31 y; median age 70 y; $n=26$, 62% female) participants took part in the study. In the younger group, most people (77/82, 94%) were right handed, 4% (3/82) were left handed, and 2% (2/82) were

ambidextrous. A total of 96% (79/82) of the participants were pursuing a graduate degree, and 4% (3/82) were pursuing a doctorate. Of the 42 older people, 30 (71%) were married, 8 (19%) were widowed, 3 (7%) were single, and the others' data could not be found.

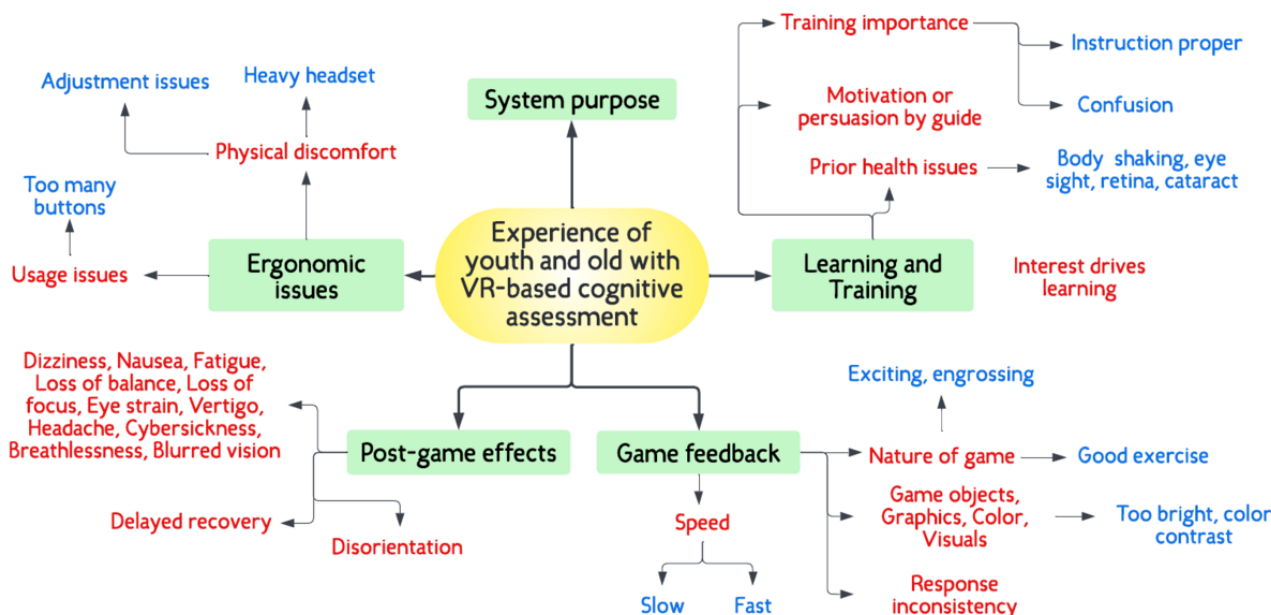
The results of the statistical comparison of the gaming, VR, and digital experience of the younger and older cohort are presented in Table 1. For all 3 measures, older people were less experienced than the younger ones. This was an expected observation as young people are relatively more aware of technology and gaming gadgets. However, strangely, the difference was lowest for VR experience. This small difference was due to the unfamiliarity of VR technology in both the younger and older groups. This comparison provides a context to interpret the results of the thematic analysis.

In total, 5 themes (Figure 4) were identified: ergonomic issues, learning and training, postgame effects, game feedback, and system purpose. We discuss each theme and substantiate it using examples from the data.

Table 1. Comparison of gaming, digital, and virtual reality (VR) experience of the older and younger cohort. Significance was assumed at $P < .05$.

| Measure | μ_{old} (n=42) | μ_{young} (n=82) | Mean difference (95% CI) | P value |
|--------------------|--------------------|----------------------|--------------------------|---------|
| Gaming experience | 2.85 | 4.06 | -1.20 (-1.68 to -0.72) | <.001 |
| VR experience | 1.52 | 2.22 | -0.695 (-1.10 to -0.293) | <.001 |
| Digital experience | 3.14 | 4.59 | -1.45 (-1.86 to -1.04) | <.001 |

Figure 4. Thematic map showing the 5 themes and their subthemes. VR: virtual reality.



Ergonomic Issues

Most participants reported physical discomfort due to the VR headset or HMD. Older adults who had poor eyesight, retina problems, or cataract surgery history reported greater discomfort and uneasiness. The VR headset is an external device that is worn on the face covering the eyes and has 2 side straps for fixing or tightening the headset with respect to the head. The high weight of this headset (500 g) was the reason for this physical discomfort.

Our observations are substantiated by previous research that has found that the weight of the HMD and high local pressure lead to discomfort and fatigue and upset the user experience [76-79]. Previous research on use of VR HMDs for underground workers suggests that the maximum acceptable mass of the HMD is 1000 g [80], but in our study, we found that participants complained of heaviness in the headset even though its weight was 500 g.

The heaviness of the headset caused discomfort during the hand-eye coordination game in both the younger and older cohorts. We believe that this discomfort was aggravated by the physical movement of hands and limbs required in the hand-eye coordination game because similar discomfort was not reported for the navigation game, which does not require any physical movement. Thus, it appears that games that require passive engagement would be more tolerable with the current weight of the headset. However, such passive engagement is not conducive to realistic cognitive assessment because real-world tasks require movement and action. Therefore, the heaviness of

the headset is detrimental to the long-term adoption and acceptance of VR-based cognitive assessment games in the general populace [77,79].

It was also found that the side straps provided with the commercial headset are not user-friendly and using them for fixing and adjusting the headset is inconvenient. The issue of adjustment of straps was reported in the younger cohort, in whom the pilot was conducted first. On the basis of their feedback, we replaced the original adjustment straps with the enhanced side-strap support provided by the KIWI design. This change improved the head adjustment for the older group, and no adjustment problems were reported in this cohort. Our observation on the original adjustment straps provided with the Oculus headset is confirmed by an opinion piece by a law, technology, and human rights attorney [81]. The author mentioned that the strap adjustment piece keeps pulling out when adjusting for different participants and is difficult to fit around traditional headgears such as turbans and hijabs.

In addition to the headset and strap problems, participants reported issues related to button use in the handheld controllers. Each Oculus handheld controller has a total of 6 buttons. The index finger is generally put on the trigger button, the middle finger is put on the gripper, and the thumb is used to control the other 4 buttons. Although the game instructions notify the use of the buttons, the participants still reported confusion with button use at runtime. Particularly in the navigation game, participants reported confusion as the game involved multiple buttons: walking, stopping, and flying. The controller buttons

do not seem naturalistic to real-world use, and some researchers indicate that VR gloves are superior [82].

However, for the hand-eye coordination game, which did not require any buttons to be pressed on the controllers, this confusion was not reported, but a peculiarity was observed wherein older people assumed that they needed to press the button to play the game. It took some time to make them realize that only controller movement was required and no buttons on the controller needed to be pressed. However, ideally, in such games, it is better to use controllers that do not have buttons.

VR gloves could appear more intuitive and naturalistic as they lessen the abstraction between the real and virtual worlds [82].

Textbox 1 shows some comments from the participants that substantiate the ergonomic issues with the headset.

Due to both the heavy headset and multiple buttons on the controllers, the participants could not seamlessly play the games. To address this, device manufacturers need to minimize the headset weight, and game developers can use the buttons on the controllers that are intuitive and aligned with natural finger use in day-to-day life.

Textbox 1. Comments from the participants on the theme of ergonomic issues.

Youths

- “People with high power in specs, may find some discomfort initially.” [Male and female participants; aged 18-21 years]
- “Headset was heavy.” [Male and female participants; aged 18-26 years]
- “Making turns in the Navigation game using controllers was not very friendly.” [Male and female participants; aged 18-21 years]
- “I had fullness of head due to the headset.” [Male and female participants; aged 19 years]
- “Too many buttons in the controller.” [Male participant, aged 18-19 years, and female participant, aged 26 years]
- “I had headset adjustment issue, due to which I had blurred vision. With spectacles, it was an added difficulty.” [Male and female participants; aged 22, 23, and 26 years]

Older people

- “I had a feeling of interference due to glasses. Without glasses, it was difficult as the headset was very heavy.” [Male participant; aged 62 years]
- “Difficult for everyone, would like to use only the computer frequently, but not the VR.” [Female participant; aged 64 years]
- “Could not play the VR Game as experienced discomfort on putting the headset. I also have retina issues so I do not want to play the game.” [Male participant; aged 69 years]
- “First time holding it, so I am very conscious and find it difficult to use.” [Female participant; aged 71 years]
- “I found the headset very heavy, and without glasses also I found it difficult.” [Female participant; aged 75 years]

Learning and Training

The second theme related to the learning and training required to play the VR-based games. Given that the VR-based experience was novel for both the younger and older groups (VR experience=1.52/5 for the older cohort and 2.22/5 for the younger cohort), learning and training is crucial. A difficult learning process and poor training might dissuade users from adopting the technology.

In our study, training was provided using a short tutorial for the VR games and controller use. Each participant had a chance to play a mini game before playing the 3 trials for each game. The mini game served as a hands-on training for the games. Both younger and older participants acknowledged that the training helped them play the games independently. Few complained of not understanding the video instructions due to audio and background noise. In these cases, extra explanations were provided, but it is essential to eliminate audio and noise from the training and learning videos. Due to playing 3 trials, the participants were able to gradually learn how to play the games.

We also realized that, in the context of VR, training must not be limited to technology-based training. For older people, training can be augmented by explanation, support, and persuasion from the game administrator. These game

administrators could be neuropsychologists, neurophysiotherapists, or neuropsychiatrists. For example, in our study, a male participant aged 73 years could not understand how to play the hand-eye coordination game despite repeated instructions. His recent cataract surgery caused him difficulty to apply the instructions to the game. However, with the patience and support of the game administrator, combined with his interest, he was able to successfully learn how to play the game independently.

However, sometimes, repeated assistance may not work if the patient has cognitive impairment. For example, in our study, a male participant aged 62 years with mild cognitive impairment kept forgetting the instructions during the game, so it was challenging to sustain learning due to his medical condition, impeding his gameplay. Therefore, according to the context, the situation, and the interest of the participant, learning and training can be customized for unique cases.

In the existing literature, very few studies have focused on the learning or training required to play VR games. We found research on using VR games for learning and teaching in academic settings [83,84], but research on the difficulty or ease of learning to operate VR and play games on it is missing. Existing studies on VR focus on its usability [85], perception [86], and adoption [87] but fail to comment on the learning and

training required to use it. The learning trajectory of VR is important to study in different population groups at whom the products are targeted, especially the older adult group.

[Textbox 2](#) shows comments from the participants to substantiate the aforementioned discussion.

From the comments in [Textbox 2](#), it is clear that youths reported fewer challenges with learning and training for the VR games and the older group faced difficulties. This difference can be attributed to aging effects on learning [88]. Accordingly, solutions and strategies need to be developed to cater to the unique learning needs of the older population.

Textbox 2. Comments from the participants on the theme of learning and training.

Youths

- “Tutorial was enough, games were easy.” [Male participant; aged 18 years]
- “Technical for first-timers.” [Male participant; aged 19-20 years]

Older group

- “Something out of routine, so found it difficult.” [Female participant; aged 65 years]
- “The introduction video voice is not clear.” [Female participant; aged 67 years]
- “The instructions in the video were fast.” [Male participant; aged 73 years]
- “The confusion was there for the first two times, later it became clear.” [Male participant; aged 73 years]
- “Was confused in the beginning, as it had been a long time.” [Female participant; aged 65 years]
- “Except for few things in the beginning, it was easy to learn.” [Female participant; aged 69 years]
- “If the person is interested, they will learn quickly.” [Male participant; aged 73 years]
- “Overall, the games were extraordinary. The guide who conducted the test was in a position to articulate well for my understanding and performance.” [Male participant; aged 72 years]

Postgame Effects

Both the younger and older cohorts reported immediate but subsiding health-related effects after the VR games. This included dizziness, nausea, fatigue, eyestrain, vertigo or headache, cybersickness, breathlessness, blurred vision, loss of balance, loss of focus, and disorientation. Participants with previous health issues such as screen strain reported relatively higher eyestrain after the VR game.

Due to these health effects, participants took some time to become comfortable after the games, normally 30 to 60 seconds, as we observed. The postgame discomforting effects were more commonly reported after the navigation game. These effects could be attributed to the nature of the navigation game, which requires no physical movement. Thus, the player has a perception of forward motion or flying (in the flying segment) in the game while they are actually standing or sitting in the real world. Due to this sensory discrepancy, there is a sense of inertia during the game and disorientation after the game. This sense of inertia seemed to have compounded over the 3 continuous trials of the navigation game, resulting in postgame disorientation and negative health-related effects.

For the hand-eye coordination game, postgame health effects were minimal in the younger and older cohorts. Unlike the navigation game, wherein a sensory discrepancy is present between the player in the game and the one in the real world, in the hand-eye coordination game, this is not so. The movements of hand and limbs expected in the hand-eye coordination game are aligned with the movement in the real world; consequently, there is no sense of disconnection experienced by the player during the game. Therefore, postgame

effects such as dizziness, nausea, and disorientation were not observed for the hand-eye coordination game. Still, tiredness and fatigue among the older group were reported, which were indicative of their physical movement during the 3 trials of the game and may not necessarily be negative.

A core reason for the postgame effects of the VR games could be the continuous administration of 3 trials. Continuous VR exposure, especially to the graphic-rich and stimulating environment of the navigation game, can intensify the negative postgame effects [89,90]. Adverse health effects after VR exposure are well documented in research. Our findings are confirmed by previous research that reports cybersickness characterized by visual fatigue, headache, disorientation, dizziness, nausea, and tiredness [91-97]. In scientific terms, these are referred to as VR-induced symptoms and effects [98]. For a detailed study of VR-induced symptoms and effects, readers can refer to the narrative review by Souchet et al [99].

In [Textbox 3](#), we substantiate the postgame effects using comments from the groups. Among the youth, all the comments on postgame effects were related to the navigation game.

Comments from the older cohort are shown in [Textbox 4](#). We noticed very few complaints of postgame adverse health effects among the older group. This is attributed to the gameplay of the hand-eye coordination game, in which no sense of disconnection or discrepancy was experienced by the player in the virtual world and the real world.

From the aforementioned discussion and examples, it is clear that sensory discrepancy or too much stimulation and continuous exposure can lead to negative postgame effects, which normally subside after some time and are not dangerous. Still, these

effects may be detrimental to the acceptance of VR games and need to be minimized.

Textbox 3. Comments from the younger participants on the theme of postgame effects.

Youths

- “Eye strain due to color in the Navigation game.” [Male and female participants; aged 18-23 years]
- “Eye strain due to headset.” [Male and female participants; aged 19-23 years]
- “Skeptic of the vision problems caused by VR.” [Male participant; aged 19 years]
- “Exhausted after the Navigation game.” [Male participant; aged 19 years]
- “Experience just like post exam—got tired.” [Male participant; aged 19 years]
- “Lost balance many times in the Navigation game.” [Male and female participants; aged 19-21 years]
- “Sense of balance is lost while in the game, headset is heavy. Reported nausea, disorientation. In the second trial removed the headset once, 3rd trial not played. Asked to be seated and play, but reported discomfort and quit.” [Male participant; aged 21 years]
- “Navigation game was disorienting a bit.” [Male participant; aged 19 years]
- “Headache, eye strain, blurry vision due to heavy usage (by the end of Trial III).” [Male and female participants; aged 18-21 years]
- “Headache during post-game form filling.” [Male participant; aged 19-20 years]
- “Initially in the beginning headache was there, improved with time.” [Male participant; aged 18 years]
- “Little dizziness in the beginning.” [Male and female participants; aged 18-19 years]
- “Dizziness is a put-off.” [Male and female participants; aged 18-21 years]
- “Head feels more heavy after the movement game and during turning motions.” [Male and female participants; aged 18-21 years]
- “Head spinning during the fly.” [Male participant; aged 19 years]
- “Cannot play for longer time.” [Male participant; aged 20 years]
- “After the game, took time to come back to the real world.” [Male participant; aged 18 years]
- “Takes time to get normal.” [Male participant; aged 19 years]
- “After the games, difficulty in walking in the real world. Could not walk in a straight line after the game.” [Male participant; aged 19 years]

Textbox 4. Comments from the older participants on the theme of postgame effects.

Older group

- “Eye strain after playing and headache.” [Female participant; aged 64 years]
- “Played only two levels of the VR game, got very tired after two trials, so wanted to stop.” [Male participant; aged 67 years]
- “Could not play the VR game as she felt dizzy.” [Female participant; aged 75 years]
- “I felt very tired and breathless and wanted to stop after the 1st level but was persuaded to try, but again I got breathless after the 2nd level.” [Female participant; aged 75 years]

Game Feedback

The game feedback differed for the 2 VR games. Most of the younger participants highlighted that the graphics in the navigation game were too bright and had high contrast. Previous research on VR games has also identified color and contrast as important factors for VR games and linked them to cybersickness [76,94]. Poor graphics such as frequent color change and highly dynamic videos are linked to visual fatigue in VR games [100,101].

When inquired about the realism of the game, participants remarked that the game objects were animated and seemed unreal. We realized that the younger participants defined game realism strictly based on its overlap with the real-world environment and objects. Although this expectation is not unjustified, we believe that it imposes a very rigid definition of

realism in the context of VR. On reflection, we realized that realism in the context of VR is a broader concept and may include real-world scenarios, but this criterion is not necessary to establish the realism of VR games. Animated game environments that mimic the nature and intensity of cognitive load observed in the real world also hold realism. Accordingly, even if the objects in the animated game environment do not duplicate real-world objects, if they can assess cognitive processes and skills similarly to real-world cognitive engagement, such animated game environment has realism. From this broader standpoint on realism, we believe that the navigation game held realism as it involved cognitive processes linked to walking, avoiding obstacles, waiting, climbing stairs, and grasping.

Realism in VR has been found to be associated with greater presence and more intense responses [102,103] and is one of the factors that determine enjoyment. Thus, it is important to consider it when designing games for cognitive purposes.

Textbox 5 presents some comments from the younger group on game feedback.

For the hand-eye coordination game, color or graphics issues were not reported by any of the group participants. In fact, a female participant aged 69 years shared that she was deeply involved in the visuals of the hand-eye coordination game. However, participants pointed out a mismatch and inconsistency between user action and game responses. Both younger and older participants complained that their hammer hits were not registered at times, due to which they lost key points. Participants also reported latency in the response to their actions, which caused lagging in the game. Both latency and lagging are known factors that relate to VR experience; however, it is believed that these are hardware issues and are less likely to occur with new HMDs [76].

Furthermore, in the older group, we found mixed reviews on the speed of the incoming cubes in the hand-eye coordination game. Some participants felt that the speed was higher, due to which they could not focus on both the colored cubes, whereas a few felt that it was too slow and could be increased. These 2

Textbox 5. Comments from the younger participants on the theme of game feedback.

Youths

- “HD Graphics could improve the user experience.” [Male participant; aged 18 years]
- “Graphics did not seem natural.” [Male participant; aged 18 years]
- “Cartoonish visual aspects, knew they were fake.” [Male participant, aged 19 years, and female participant, aged 21 years]
- “Colors were too bright, too many things were moving.” [Male and female participants; aged 18-19 years]
- “Lot of stimulus was there.” [Male participant; aged 19 years]
- “Interaction with the environment was not realistic.” [Male participant; aged 19 years]
- “Photorealism is lacking.” [Male participant; aged 19-21 years]
- “Graphics not that good, color saturation unlike the real world in the Navigation game.” [Male participant; aged 22 years]

contrasting views indicate subjectivity in the perception of the game but also call for dynamic adjustment of the speed of incoming cubes. Such enhancement could greatly improve the user experience of the game. Moreover, given the frailty in the older group, we also noticed that the hand-eye coordination game could be made more flexible by introducing a seated gaming arrangement.

Finally, our broader definition of realism was also confirmed in the hand-eye coordination game, wherein participants reported that the game felt natural and real. Even though no one plays such a game in the real world, the movements, such as lifting a hammer and moving it sideways, up, and down, are typical of the real world. A sense of sensory synergy (ie, similar movements in the real and virtual world during gameplay) also contributed to a sense of realism in the hand-eye coordination game. Our views on realism in the VR games are confirmed in a research paper that calls for deeper understanding of realism and mentions that it relates to both the illusion and immersion components [104]. Thus, a multisensory environment could be more immersive as it engages the senses of the person just like the real world.

Textbox 6 presents some of the comments on the hand-eye coordination game from the older cohort that substantiate this theme.

Textbox 6. Comments from the older participants on the theme of game feedback.

Older cohort comments on the hand-eye coordination game mechanics

- “Getting annoyed, sometimes, even when hitting correct, it did not smash. The logic of cube hitting was not consistent for all the cubes.” [Female participant; aged 68 years]
- “The speed was so fast it required to be fast, but that was causing confusion.” [Male participant; aged 73 years]
- “The incoming cubes were too fast, and sometimes when it is left and other is coming at the right, it is difficult to move fast.” [Male participant; aged 68 years]
- “When the game is slow, it is ok, but not when it is fast.” [Male participant; aged 78 years]
- “As soon as I hit red, blue came fast, that’s why I lost so many points. Felt like brain was not acting properly when using two hammers.” [Male participant; aged 73 years]
- “Needed practice, left hand not as fast as the right so took time to be fast.” [Female participant; aged 67 years]
- “The cube could move faster, as it is giving time to think, could be challenging if it moved faster.” [Male participant; aged 77 years]
- “Difficult to coordinate with both the hands, one hand is better.” [Female participant; aged 65 years]
- “As level increases, complexity should be high so that it is interesting and keep the user hooked.” [Male participant; aged 74 years]
- “Was very enjoyable, did not feel like it was a test.” [Female participant; aged 67 years]

Older cohort comments on the hand-eye coordination game in general

- “Interesting experience, hand fun. No changes required, good as it is.” [Female participant; aged 63 years]
- “The coordination was a good exercise.” [Female participant; aged 63 years]
- “The game was fun and the music in the game was fun.” [Female participant; aged 68 years]
- “Very much liked it. Nothing was distracting.” [Female participant; aged 69 years]
- “It was a good experience.” [Male participant; aged 74 years]
- “Because the game is artificial environment, it will look artificial.” [Female participant; aged 63 years]
- “If there is an option to let you sit and play, then that would be good.” [Female participant; aged 71 years]

System Purpose

Both younger and older participants were curious about the purpose of the VR games. At the beginning of the trial, we informed the participants about the games, how to play them, and how participant performance would be mapped to their cognitive abilities or performance. This explanation and training were aimed at making them aware of the subsequent game-*cum*-assessment sessions. After the session, participants were more inquisitive about these games having experienced them directly.

Indeed, the purpose or utility of VR games for users is important because they need to decide whether to accept them for their hedonistic or utilitarian purposes [52,53]. In fact, in the initial stages, the excitement and novelty drove their participation, but going forward, the system’s purpose would define the continuous engagement with the games. Therefore, the system’s purpose is a very important theme in the context of VR-based cognitive assessment games. The purpose indicates the perceived usefulness, which eventually influences their adoption as per the technology acceptance model [105].

A meaningful purpose engenders a positive attitude among the users and key stakeholders and determines the long-term

adoption of VR games [106,107]. Thus, after the initial excitement and hedonistic pleasure has plateaued, VR-based games will have to prove their efficacy [57], and a clear purpose can accomplish this.

Textbox 7 shows comments to substantiate the theme of system purpose.

In the older group, no one inquired about the system purpose. It appears that, for them, engagement and an opportunity to try something new were more valuable than purpose, and similar findings have been obtained previously [108-111]. This perspective is advantageous to develop more engaging, active games in the VR environment for older people, especially for rehabilitation and skill building. Thus, a trade-off between utilitarian and hedonistic motives was observed in the 2 groups. Key stakeholders must maneuver their strategies to serve these differential motives.

We have discussed in detail the 5 prominent themes that were identified by analyzing the interview responses of the younger and older groups. We understand the importance of linking these findings to real-world actions and decisions; thus, in the next section, we discuss the implications of the results.

Textbox 7. Comments from participants on the theme of system purpose.

Youths

- “I do not know what the system is for as of now. I do not know why I would use it.” [Male participant; aged 19 years]
- “Not sure what the system is aimed at.” [Male participant; aged 18 years]
- “I won’t use it on a daily basis. Once or twice a week.” [Male participant; aged 20 years]

Implications of the Results

In this section, based on the results of the thematic analysis, we provide precise actionable suggestions relevant to 4 key stakeholders: researchers, game developers, businesses, and neuropsychology and allied practitioners.

Researchers

From the results of the thematic analysis, it is evident that all participants were eager to engage with the VR-based games. To translate this initial eagerness into long-term engagement, researchers need to identify gaming concepts, designs, environments, and abstractions that can be used for developing cognitively stimulating games. Given the limitation of ecological validity in the traditional pen-and-paper-based neuropsychological assessments [8-10,112-114] and the comments on game realism by the participants, researchers can design gaming ideas that resemble real-world situations and mimic the cognitive load and decision-making required for real-world tasks. Such an approach could potentially provide more informed assessment of the real-world-relevant cognitive abilities and deficits of the person. To this end, interaction with customers and brainstorming with other researchers in the fields of neuroscience, computer science, customer satisfaction, and human psychology is essential [115,116].

Game Developers

Game developers are often excited about the special effects, high-end graphics, and engaging music that make their games unique. However, in the context of cognitive assessment and rehabilitation, simplicity and intention are key factors that game developers must remember. In the navigation game, button use, graphics, and multiple stimuli caused a lot of confusion and adverse postgame effects, due to which the overall experience was less enjoyable. On the other hand, the hand-eye coordination game was simple, intentional, and very intuitive; consequently, both the younger and older cohorts enjoyed the overall experience. Taking a cue from these findings, game developers must prioritize simple and intuitive gameplay for cognitive engagement. This approach would create games that can flow on their own while engaging the player. This sense of flow is important for the players as it is linked to intention to use [117-120]. Bad graphics, bugs, overstimulated environments, and response-feedback inconsistency can lead to loss of flow and discomfort [45,73,121]. Therefore, game elements must be designed to promote a natural flow in the game. Knowledge of such elements and their quality can be obtained through regular testing among the target users.

Businesses

Recently, several business enterprises centered on cognitive assessment and rehabilitation have emerged. To truly have an

impact on the lives of people, these enterprises need to focus on some key takeaways from this thematic analysis. The most important takeaway is purpose and meaning. While the technology and game thrill may excite the players momentarily, meaning and the long-term impact of the game will lead to sustainable adoption.

Especially among the younger group, game utility determines adoption. However, in the case of the older group, entertainment and enjoyment seem to have an edge over utility. Still, we believe that the 2 do not have to be mutually exclusive. Both utilitarian and hedonistic aspects can be integrated in cognition-assessing games. For example, our hand-eye coordination game was both useful and enjoyable, and its feedback from both groups was very positive.

Second, manufacturing businesses need to rethink the VR headset and controller design [122,123]. The current weight of the VR headset [124,125] and the adjustment straps can cause issues such as fatigue, headache, and discomfort. Therefore, lightweight HMDs and integrated headsets such as the one with KIWI support are better than soft band straps [124]. In addition, controller buttons must be designed to minimize interference and confusion in use; this improvement would lead to more intuitive use of the controllers, promoting flow in the game [118,119]. Thus, the ergonomic issues directly relate to HMD manufacturers and motivate them to make human-centered design decisions [126-128].

Neuropsychology and Allied Practitioners

VR-based games for cognitive assessment and rehabilitation are often used in neuropsychological clinics or laboratories. Findings of our thematic analysis are also relevant to practitioners in these settings. The learning and training theme results emphasize using quality instructions for communicating and demonstrating the game rules. In case audio and video instructions do not suffice, facilitators can explain the instructions to the patients. Our results also demonstrate the positive impact of motivation and persuasion on the patients when they have qualms or apprehension about the games. Neuropsychology practitioners must also be mindful of previous health issues of the patients while administering games to them. Thus, an element of compassion and kindness, not amounting to infantilizing or spoon-feeding, is essential while administering the games, especially in the older cohort.

Tabulated Summary of the Theme and Their Relevance to Key Stakeholders

The applicability of the theme results to different sectors were tabulated (Textbox 8). It is clear that most of the themes are relevant to all stakeholders. Thus, all 4 key stakeholders must

work in synergy to innovatively use VR technology for cognitive assessment and rehabilitation.

Textbox 8. Themes and the stakeholders directly or indirectly linked to them.

Theme and applicability sector or stakeholders

- Ergonomic issues: hardware manufacturers and businesses
- Learning and training: game developers, businesses, researchers, and neuropsychology and allied practitioners
- Postgame effects: game developers, businesses, researchers, and neuropsychology and allied practitioners
- Game feedback: game developers, researchers, and neuropsychology and allied practitioners
- System purpose: game developers, businesses, researchers, and neuropsychology and allied practitioners

Discussion

Principal Findings

In our study, we found that most of the problems faced by the participants were due to headset weight, adjustment straps, game graphics, or motion in the game. Several previous reviews on VR games discuss and describe these challenges associated with VR games but fall short of investigating the reasons behind them [47,48,50]. Such a limited approach does not contribute to improved user experience because we do not know which things to mend and which features to continue with. Furthermore, VR technology is touted to disrupt the health care service sector; therefore, it is crucial that direct human feedback is obtained because any other secondary means, such as literature reviews and web-based reviews [45], risk half-truths.

We also found that different users have different reasons to adopt the product. While both the younger and older cohorts attested to the entertainment and excitement part of it (ie, the hedonistic aspect of the game), the younger group also expressed curiosity about its use and purpose. Previous studies exploring the hedonistic [44] versus utilitarian aspects [48] of VR games provide a general description of these but do not comment on who may be more inclined toward the hedonistic or utilitarian aspects. From our study, we observed that older adults may be more attracted to the hedonistic aspect of the game, whereas the youth may be lured by it temporarily and anticipate utility in the long run. We believe that this insight is extremely useful for evidence-based translation of cognition-assessing VR games.

Our findings on issues of bugs, highly saturated graphics, and confusion due to multiple controller buttons are substantiated by a thematic analysis based on web reviews [45]. Concerns about realism, display quality, and game interface found in our work form the most prominent aspects of VR-based research [46]. Overall, our findings are confirmed by existing research on VR games. However, unlike previous studies that merely report the concerns and advantages of VR-based games, we have raised questions that emphasize the importance of uncovering the causal factors behind these concerns and advantages. Ultimately, the knowledge of these causal factors paves the road for improved experiences with VR game-based cognitive assessment.

Especially with a novel technology such as VR, there is a lot of responsibility on all the stakeholders as there is a risk of addiction [129] and adverse effects [130]. Our discussion on

the implications of the study for the stakeholders will indirectly help with the improvement of VR games, thereby assisting in enhanced cognitive assessment and rehabilitation. However, it must be remembered that novel technology tools must be handled with a sense of accountability wherein user interests and safety are superior to commercial interests.

Conclusions

We presented a thematic analysis of the interview responses of 82 younger (aged 18-28 years) and 42 older (aged >60 years) participants after they played VR-based cognitive assessment games. A total of 5 main themes were identified and discussed: ergonomic issues, postgame health effects, game feedback, learning and training, and system purpose. We found that the younger and older groups had different needs and expectations from these games. For long-term engagement, the younger group prized meaning and utility, whereas the older group liked the enjoyment and entertainment aspects. We also found that the heaviness of the headset, cybersickness, and visual fatigue are the most common problems faced in both groups. However, these problems are less painful if the game environment is not hyperstimulating and has warmer color graphics. In addition, games with less conflict between the real-world sensory information and the VR environment movement are more enjoyable than those with sensorimotor conflict.

We also discussed the implications of these themes for 4 key stakeholders in the field: researchers, game developers, businesses, and neuropsychology and allied practitioners. Researchers must identify real-world concepts that can be used to design ecologically valid games that engage the senses and cognitive abilities similarly to the real world. Game developers need to develop games that are simple, intentional, exciting, and able to flow on their own. Business enterprises must focus on giving a purpose and meaning in these cognitive assessment games to ensure long-term use and impact. Manufacturing businesses must address the issues related to the heaviness of the headset, unfriendly side adjustment straps, and multiple controller buttons to simplify the use experience during assessment. Finally, neuropsychology and allied practitioners play the most important role of administering the VR-based games to the patients and, thus, must be willing to explain these games to patients and use persuasion and compassion during the process. Finally, all stakeholders must collaborate together to develop high-impact games for cognitive assessment and remember to cater the solutions to the unique needs of the target population.

In conclusion, our thematic analysis contributes to the acceptance research on VR-based cognitive assessment games because it compares the feedback from the younger and older groups in primary settings. The discussion on the implications of the findings for the stakeholders provides unique perspectives on translating the findings to the real world. The limitation of the study is the lack of follow-up on game use and adaptation. We believe that a longitudinal monitoring of user attitudes and perceptions would provide a stronger understanding of acceptance and adoption of VR games for cognitive assessment. As a future direction, researchers are advised to monitor game use in the long term, preferably 6 months. In addition, we tested these games in only 2 age groups (18-28 and >60 years) and,

therefore, recommend also testing and piloting these games in middle-aged groups (30-50 years). These results would provide more clarity on the overall effectiveness of the VR games to capture age-related cognitive decline. Finally, we piloted these games in healthy groups, so it is strongly suggested to obtain feedback from people with mild cognitive impairment, who are at a greater risk of developing dementia.

Finally, we believe that VR is an immensely novel and exciting tool and it is easy to be swayed by the thrill of technology. Therefore, it is important to remind ourselves to use it in a responsible manner such that human safety and benefits are honored over purely commercial and monetary interests.

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Authors' Contributions

YB conceptualized the study, collated interview data, conducted the thematic analysis, and wrote the manuscript. VB supervised the study and reviewed the manuscript for intellectual content. Both authors approve of the manuscript.

Conflicts of Interest

None declared.

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Abbreviations

BITS: Birla Institute of Technology and Science

HMD: head-mounted display

VR: virtual reality

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