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Metaverse-Based Psychiatric Consultation for Youths With Mental Health Conditions: Qualitative Descriptive Feasibility Study

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Abstract

Background: Youth mental health is a global public health priority, with rising rates of anxiety and depression, particularly after the COVID-19 pandemic. Despite the early onset and substantial burden of mental disorders in this age group, young people are less likely than adults to seek professional help and face barriers such as workforce shortages, stigma, and low mental health literacy. Although efforts such as outreach initiatives and school-based programs have been implemented, innovative and scalable solutions remain limited. Digital technologies, including the metaverse, may offer flexible and stigma-reducing approaches to mental health care; however, evidence regarding their real-world feasibility and acceptability is scarce.

Objective: This study investigated the feasibility and user experience of metaverse-based psychiatric consultations for young people with mental health conditions.

Methods: We conducted a qualitative descriptive feasibility study at a single academic institution in Yokohama, Japan, between July and November 2023. A total of 26 participants aged 16 to 25 years (mean age 19.9, SD 2.4; 15 male, 7 female, 3 nonbinary, 1 no response) who self-identified as having mental health concerns were recruited from local psychiatric clinics, schools, universities, and social media. Reported concerns included anxiety, depressive symptoms, and autism spectrum disorder traits. Participants completed a 30- to 40-minute one-on-one metaverse-based consultation with a psychiatrist using avatars in a virtual reality environment, followed by semistructured interviews exploring feasibility, usability, and user perceptions. Data were analyzed using thematic analysis, and data collection continued until no substantially new themes emerged. Reporting followed the APA Journal Article Reporting Standards for qualitative research.

Results: All participants completed the study without any adverse psychological events. Five participants experienced minor, transient physical discomfort (eg, headaches and virtual reality–related sickness), which resolved without medical intervention. Thematic analysis identified 3 primary domains: perceived psychological safety through avatar-mediated interaction, enhanced spatial presence facilitating rapport, and increased autonomy within the virtual environment. Metaverse consultations were perceived as particularly beneficial for individuals experiencing interpersonal anxiety, sensory sensitivities (including autism spectrum disorder traits), difficulty leaving home due to psychiatric conditions, psychological resistance to traditional psychiatric settings, or discomfort with physical self-presentation.

Conclusions: This qualitative descriptive feasibility study provides preliminary evidence that metaverse-based psychiatric consultations are a feasible and acceptable approach for supporting young people with mental health conditions. Unlike conventional telepsychiatry based on videoconferencing, the use of avatar-mediated interaction and immersive virtual environments may reduce psychological barriers related to self-presentation, stigma, and interpersonal anxiety for specific subgroups of youth. These findings suggest that metaverse-based consultations can be effectively integrated into clinical pathways as a complementary, “low-threshold” access point within stepped or hybrid care models, ultimately bridging the gap between initial help-seeking and formal psychiatric treatment.

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KEYWORDS

mental health; metaverse; youth mental health; virtual reality; telepsychiatry

Introduction

Youth mental health is a critical global issue that remains complex and challenging. Reports indicate that 1 in 5 young people experiences anxiety, and 1 in 4 faces depression due to factors such as poverty and shifts in lifestyle patterns [1,2]. This prevalence doubled before and after the COVID-19 pandemic [3]. With more than 25% of mental disorders beginning before the age of 25 years [4] and the significant socioeconomic impact of these conditions [5], the need for effective mental health care for young people is clear. Despite this, young people are less likely to seek professional support for mental health problems than older age groups and often struggle to access timely and high-quality mental health services (MHSs) [6-8]. Several factors contribute to this gap between demand and supply, including physical barriers such as the shortage and geographic maldistribution of child and adolescent psychiatrists, as well as psychological barriers such as stigma and low mental health literacy [9-11]. Although initiatives, including school-based psychoeducation, peer training, and outreach programs, have been implemented to mitigate these barriers, a breakthrough solution remains elusive [6,12-14], underscoring the need for further research.

As an innovative response to these challenges, information and communication technology (ICT) has become increasingly central to youth mental health care. McGorry et al [9] have called for a redesign of youth MHSs and conceptualized youth psychiatry as a distinct discipline, emphasizing early intervention, co-designed youth-friendly services, integration of digital technology with human support, and an extended service boundary up to age 25. Consistent with this framework, ICT-based services are expected to enhance accessibility, reduce stigma, and provide flexible, developmentally sensitive support for late adolescents and young adults, whose daily communication and help-seeking increasingly occur online [9,15]. However, recent systematic reviews caution that the real-world impact of digital youth MHSs may be constrained by usability burdens, uneven engagement, and variable acceptability across diverse youth populations [16]. Accordingly, feasibility studies in novel, youth-centered digital environments are a critical step toward identifying formats that young people can realistically and sustainably use.

One emerging ICT modality is the metaverse, broadly defined as a persistent, shared virtual space in which users interact through avatars within immersive (eg, virtual reality [VR]/mixed reality) or nonimmersive environments [17,18]. Unlike stand-alone VR or augmented reality applications that provide isolated, session-based experiences, metaverse environments are typically continuous, socially interactive spaces in which users can maintain identity, customize self-representation, and engage in repeated or ongoing interactions over time. These environments may include synchronous communication, spatialized presence, and customizable virtual settings, allowing users to experience a sense of copresence and embodiment beyond conventional video-based teleconferencing [19].

In youth mental health contexts, these features may be particularly relevant. Recent reviews of immersive and metaverse-based digital therapies suggest potential experiential advantages over conventional telepsychiatry; however, robust empirical evidence remains limited and heterogeneous [18]. Avatar-mediated interaction and the option to engage from a private physical location may lower the psychological threshold for help-seeking and support continued participation, as suggested by early metaverse-based or VR-enabled support initiatives [17,18,20]. In Japan, for example, emerging initiatives in some cities use VR-based support services for individuals with social withdrawal (Hikikomori) [20], exploring approaches to reduce stigma and facilitate access to support. The metaverse could extend these efforts internationally by offering an alternative environment in which young people can seek help discreetly and interactively while maintaining a sense of autonomy.

However, empirical evidence on the feasibility, acceptability, and ethical implementation of metaverse-based MHSs, such as psychiatric consultations for young people, remains limited, particularly in real-world clinical contexts. This study, therefore, aims to assess the feasibility of metaverse-based psychiatric consultations tailored for young people with mental health conditions, with a focus on user experience, usability, and implementation considerations. The findings will guide the development and implementation of future youth MHS, addressing key barriers to access and engagement.

Methods

Research Design Overview

This study employed a qualitative descriptive study to assess the feasibility of metaverse-based psychiatric consultations for youths with mental health conditions. Semistructured individual interviews were conducted following the consultations to explore participants' experiences, perceived usability, and acceptability of the intervention.

Study Participants or Data Sources

Participants were young people aged 16 to 25 years who self-identified as experiencing mental health conditions. The research team consisted of psychiatrists and mental health professionals with clinical experience in youth mental health care, as well as researchers with expertise in digital mental health and qualitative research. These backgrounds informed the study design, particularly the focus on feasibility, acceptability, and ethical considerations of metaverse-based psychiatric consultations.

Some participants were recruited from clinical settings where members of the research team were involved in their care. In such cases, the clinicians who had an existing therapeutic relationship with a participant did not conduct the postconsultation interviews and were not involved in the qualitative data analysis for that participant. This role separation was implemented to minimize potential power imbalances, social desirability bias, and undue influence on participants' responses.

For participants recruited through educational institutions or social media, no prior relationship with the research team existed before study participation. All participants were informed that

participation was voluntary, would not affect their clinical care or educational standing, and that they could withdraw at any time without consequences. These measures were taken to ensure ethical integrity and to support open and honest expression during the research process.

Participant Recruitment

Recruitment Strategy

Participants were recruited between July and November 2023 through multiple channels, including flyer distribution at Yokohama University Hospital, nearby clinics, local universities, high schools, community support organizations, and announcements on social media platforms. Recruitment materials briefly described the study as an opportunity to experience a metaverse-based psychiatric consultation and to share feedback about the experience. Interested individuals contacted the research team directly and were screened for eligibility.

All participants received written and verbal explanations of the study procedures, potential risks, and the voluntary nature of participation. Written informed consent was obtained prior to study participation; for participants younger than 18 years, consent was also obtained from legal guardians in accordance with institutional review board requirements. Participants were compensated with a gift card valued at approximately US $35 (¥5000).

The target sample size was determined based on the exploratory aims of a qualitative descriptive feasibility design rather than statistical power considerations. A total of 33 individuals expressed interest in participation. Of these, 1 individual did not meet the inclusion criteria, 5 were lost to contact prior to providing informed consent, and 1 was unable to participate due to their condition on the scheduled day. Consequently, 26 participants completed the metaverse-based consultation and postconsultation interview.

Recruitment and data collection were concluded when thematic convergence was observed during qualitative analysis, and no substantially new themes emerged in later interviews, indicating that the sample size was sufficient for the aims of this feasibility study.

Inclusion and Exclusion Criteria

Eligible participants were individuals aged 16 to 25 years at the time of consent, who were aware of their mental health conditions and able to provide written informed consent in Japanese. Individuals currently receiving treatment at a psychiatric medical institution without permission from their primary physician were excluded from participation.

Data Collection

Setting

The study was conducted in a meeting room on the Yokohama City University campus.

Baseline Assessment

As a baseline assessment, the participants completed a self-administered questionnaire consisting of 4 parts: (1) mental and physical conditions, (2) living conditions over the past 3 months, (3) internet usage, and (4) perceptions of mental health and psychiatry.

Metaverse Environment Setup and Technical Support

After the baseline assessment, the participants entered the metaverse environment under the guidance of technical staff, wearing VR goggles and using a controller. Since the participants were unfamiliar with metaverse operations, the technical staff provided detailed instructions for fitting the goggles, launching the application, and logging in.

For this study, experimental worlds and avatars were set up on commercially available metaverse applications, VRChat and Workrooms. VRChat is a social VR platform that allows users to create, share, and explore user-generated virtual worlds through customizable avatars, fostering social interaction and creative expression in immersive settings. In contrast, Workrooms is a virtual collaboration tool designed for professional and educational use, enabling users to hold virtual meetings in shared spaces with avatars and facilitating interactive discussions, presentations, and collaborative tasks. These applications provided structured and flexible virtual spaces suitable for the purposes of this study.

The virtual environments included 3 distinct spaces: an outer space environment, a hospital examination room, and a meeting room with selectable views of a beach or mountains. The avatars included both human and nonhuman fictional characters, providing participants with diverse ways of interacting and expressing themselves. Figure 1 illustrates one of the settings and avatars used in the study.

Figure 1. Overview of the metaverse-based psychiatric consultation process for youth with mental health conditions (N=26), conducted at Yokohama City University Hospital between July 2023 and November 2023. The image illustrates a participant and a clinician wearing head-mounted displays and engaging in interaction via avatars.

Metaverse Psychiatric Consultation

The metaverse consultations were conducted one-on-one in private virtual rooms with a psychiatrist, who also wore VR goggles and appeared as an avatar from a remote location. The psychiatrists included both male and female professionals with an average of 19 years of clinical experience.

Each consultation lasted 30 to 40 minutes and followed a semistructured framework resembling a standard initial psychiatric consultation. The consultation consisted of 5 phases. First, the psychiatrist introduced themselves via their avatar and explained the goals and structure of the session, allowing time to establish rapport and ensure that the participant felt comfortable in the virtual environment. Second, the psychiatrist reviewed the participant's medical and life history, including prior diagnoses, treatments, daily routines, relationships, and environmental stressors. Third, the session focused on symptom observation and assessment, during which participants described their current mental health concerns while the psychiatrist observed verbal and nonverbal cues through avatar-mediated interaction. Fourth, tailored guidance and recommendations were provided, including coping strategies, lifestyle adjustments, and referrals to additional mental health resources when appropriate. Finally, the session concluded with a summary of the discussion and an opportunity for the participant to ask questions or provide feedback.

The consultations were designed to balance structure and flexibility, providing participants with a supportive environment to explore their mental health concerns in a novel virtual setting. During the session, the participants navigated the 3 distinct spaces within the metaverse environment alongside the psychiatrist and interacted via various types of avatars. Technical staff members were available to assist as needed, ensuring a seamless and accessible experience.

Postconsultation Interviews

After the metaverse consultation, participants were individually interviewed to explore their experiences and perceptions of the metaverse consultation. The semistructured interview guide used in this study was developed specifically for this project. An English version of the interview form is provided in Multimedia Appendix 1 for reference. The interviews explored several key areas, including the usability of the metaverse devices, any physical or psychological discomfort experienced, acceptance compared with face-to-face consultations, perceptions of individuals or situations in which metaverse consultations may be beneficial, and implementation-related requirements or concerns.

Following the participant interviews, the psychiatrists who conducted the consultations, along with members of the research team—including psychiatric social workers and a nurse—engaged in structured discussions regarding usability, expectations, and implementation challenges. These discussions addressed the functionality and user experience of the metaverse platform, technical considerations, perceived differences between metaverse and face-to-face consultations, compatibility with participant characteristics and symptom profiles, and additional observations noted during the study.

The reporting of this study conforms to the COREQ (Consolidated Criteria for Reporting Qualitative Research) guidelines (Checklist 1) [21].

Data Analysis

Qualitative Analysis Strategy

The interview data were analyzed via thematic analysis following established qualitative research methodologies. First, all interviews were transcribed verbatim to ensure accuracy. The transcripts were then reviewed multiple times to facilitate familiarity with the data and identify potential patterns.

All interview transcripts were reviewed in full by the first author (MI), who performed line-by-line coding to identify meaningful units of text. Codes were generated inductively from the data and iteratively refined in consultation with 2 coauthors (JF and NT) to enhance credibility. Codes were clustered into categories, and higher-order themes were developed through repeated team discussions until consensus was reached.

Initial coding was conducted by systematically highlighting recurring phrases, concepts, and key statements. These codes were grouped into broader categories that represented emerging themes. To enhance rigor, the themes were independently reviewed and refined by multiple researchers to ensure consistency and reduce bias.

The analysis focused on 3 primary domains: the usability of the metaverse platform, the acceptance of metaverse consultations in comparison with face-to-face interactions, and the identification of participant characteristics or conditions for which metaverse consultations may offer particular advantages, such as social anxiety or sensory sensitivities.

Methodological Integrity

To ensure trustworthiness, we maintained an audit trail of coding decisions, documenting how codes were generated, refined, and grouped into themes. Triangulation was achieved through iterative discussions among the research team, allowing for verification and consensus in data interpretation. Representative quotations were included in the *Results* section and labeled with participant numbers to illustrate key themes and to provide transparency between the participants' voices and the researchers' interpretations.

Data collection was concluded when data saturation was reached, defined as the point at which no new themes or insights emerged from the interviews. No substantially new themes emerged in the latter part of the interviews. Thus, we consider the sample size sufficient for the exploratory aims of this qualitative feasibility study.

This study was conducted and reported in accordance with the APA Journal Article Reporting Standards for qualitative research [22].

Ethical Considerations

This study was conducted in accordance with the Declaration of Helsinki and the Ethical Guidelines for Life Science and Medical Research Involving Human Subjects, established by the Ministry of Education, Culture, Sports, Science and Technology and the Ministry of Health, Labour and Welfare of Japan (partially revised in 2023). The study protocol was approved by the institutional review board of Yokohama City University, Japan (approval number F230400055). Written informed consent was obtained from all participants prior to their inclusion in the study; for participants younger than 18 years, additional consent was obtained from their legal guardians along with participant assent, where applicable. To ensure privacy and confidentiality, all study data were deidentified during handling and analysis, and interview transcripts were meticulously reviewed to remove any personal identifiers. Participants were compensated for their time with a gift card valued at approximately US $35 (¥5000). Regarding the visual materials, this manuscript includes images of staff members demonstrating the metaverse consultation environment. All identifiable individuals in these images provided explicit written informed consent for the publication of their likeness, and the relevant consent forms are available for verification upon request.

Since this study was conducted as an observational study, clinical trial registration was not applicable.

Results

The results presented below were derived through thematic analysis of postconsultation interviews, identifying common patterns across participants' responses.

Baseline Characteristics

A total of 26 young people were assigned from a pool of 33 volunteers. One individual was excluded for not meeting the inclusion criteria, 5 lost contacts before providing informed consent, and 1 could not participate because of his condition on the day. Table 1 summarizes the baseline characteristics, while Table 2 presents the results of the baseline assessments of the participants. The mental and physical conditions of the participants varied, with many expressing difficulties in social interactions, feelings of isolation, and discomfort in seeking support from others. Most participants reported frequent internet use, although their levels of social engagement and self-care practices differed. All participants owned internet-enabled devices, and most used the internet daily. However, some participants acknowledged neglecting essential tasks due to internet use, whereas others reported difficulties in limiting their internet usage. The participants' initial impressions of the metaverse also varied. While only a minority had extensive knowledge or prior experience with the metaverse, many expressed curiosity. Their views on associating with individuals who had a history of psychiatric treatment ranged widely, with some expressing comfort and acceptance, whereas others showed apprehension or stigma toward mental health issues.

Table . Baseline demographic and clinical characteristics of youth participants with mental health conditions (N=26) in an observational feasibility study of metaverse-based psychiatric consultation conducted at Yokohama City University between July 2023 and November 2023.

Characteristic	Description
Age (y), mean (range)	19.9 (16-25)
Gender	
Male	15
Female	7
Nonbinary	3
No response	1
Recruitment sources	Yokohama City University Health Management Center, medical students and junior residents, outpatient of University Hospital and neighborhood clinics, participants from other survey of our research team, neighborhood private high school, Facebook
History of psychiatric treatment	
Yes	22
No	4

Table . Summary of baseline clinical assessments, including psychological symptoms and functional status, of youth participants (N=26) prior to the metaverse-based psychiatric consultation.

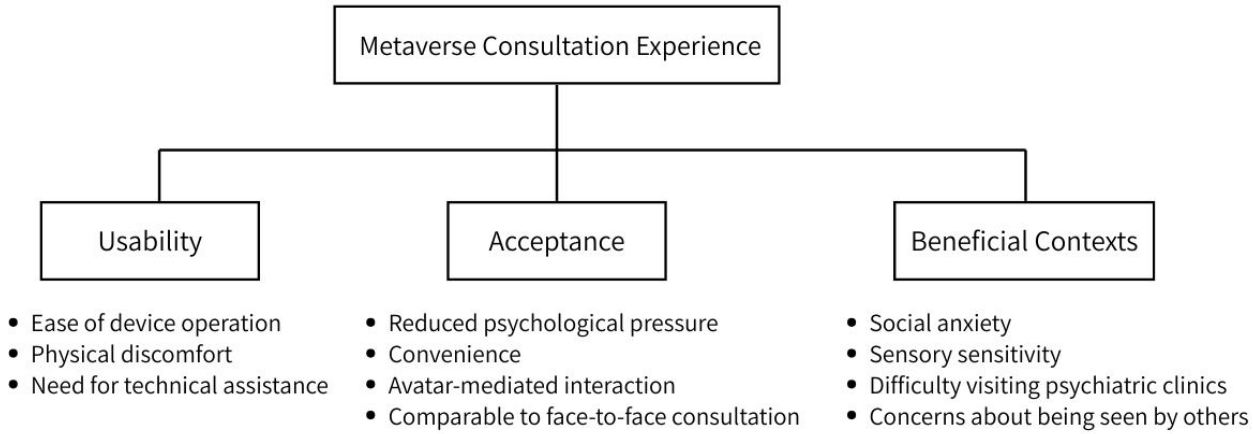
Aspect of assessment	Summary of findings
1. Physical and psychological condition	
Perceived health issues	Most participants (21/26, 80%) indicated concerns about their physical or mental health, with common issues including insomnia, social anxiety, general anxiety, depression, learning disabilities, difficulty speaking with others, and lack of motivation.
Comfort being in social situations	Nearly two-thirds (18/26, 68%) reported discomfort being in front of others, and 64% (17/26) felt uncomfortable talking with strangers, indicating significant social anxiety.
Help-seeking behavior	Approximately 65% (17/26) reported that they seek advice when facing problems, primarily consulting family, friends, teachers, or medical staff.
Sense of social connection	Mixed responses: 50% (13/26) reported sometimes feeling a lack of social connections, while others felt relatively neutral or disagreed with feelings of isolation.
Feelings of exclusion and isolation	Most participants (20/26, 77%) felt neither excluded nor isolated, suggesting a generally stable sense of belonging, despite some individual cases of feeling isolated or left out.
2. Living condition of the past 3 months	
Frequency of going out	Most participants went out frequently, with 73% (19/26) going out at least once a week, while 27% (7/26) went out less frequently.
Conversations with family members	The majority (23/26, 88%) reported daily conversations with family, indicating strong familial interaction.
Conversations with nonfamily members	Over half (20/26, 77%) had conversations with nonfamily members at least weekly, suggesting moderate social interaction outside the family.
Ability to maintain a regular routine	Only 27% (7/26) of participants maintained a regular routine daily or several times per week, with the remainder struggling to do so consistently.
Sufficient sleep	Approximately half (13/26, 50%) reported receiving sufficient sleep almost daily or several times per week, while others reported inconsistent sleep.
Frequency of bathing or showering	Nearly all participants (24/26, 92%) bathed or showered daily, indicating consistent personal hygiene practices.
Concentration on work or studies	Only 27% (7/26) could concentrate on work or studies consistently (daily or multiple times per week), with others facing challenges in concentration.
Engagement in nonwork/study activities	Most participants (16/26, 61%) engaged in hobbies, sports, or social activities at least once a week, while others were less active.
3. Internet usage	
Access to internet-enabled devices	All participants (26/26, 100%) owned internet-enabled devices, such as computers, smartphones, or gaming consoles.
Frequency of internet use	Nearly all participants reported daily internet use, indicating high internet engagement.
Neglect of responsibilities due to internet use	A majority (19/26, 73%) sometimes or always neglected responsibilities due to internet use, with only one participant reporting no impact.
Making new connections online	Around half (12/26, 46%) reported occasionally or frequently making new connections online, while 27% (7/26) never made new connections through the internet.
Difficulty reducing internet use	Nearly half (12/26, 46%) indicated difficulty reducing internet use, with the remainder having little to no issues in managing their usage.
Familiarity with the metaverse	Knowledge about the metaverse varied, with 46% (12/26) reporting some familiarity, while the rest indicated limited or no knowledge.
Experience with the metaverse	Only a small portion (6/26, 23%) had direct experience with the metaverse, indicating it was relatively new to most participants.
4. Attitudes toward mental health and psychiatry	

Aspect of assessment	Summary of findings
Friendship with individuals who have seen a psychiatrist	Most participants (23/26, 88%) expressed openness, agreeing that they could become close friends with someone who has sought psychiatric care.
Trust in individuals with a history of psychiatric hospitalization	A majority (19/26, 73%) believed that individuals with past psychiatric hospitalization are just as trustworthy as others.
Perception of psychiatric treatment as a personal failing	Most participants (22/26, 85%) disagreed with the notion that seeking psychiatric help is a sign of personal failure.
Reluctance to hire individuals with psychiatric history	Over half (17/26, 65%) felt that many people would be reluctant to hire someone with a history of psychiatric treatment, reflecting a perceived societal stigma.
Willingness to date someone with a history of psychiatric treatment	Around half (14/26, 54%) were neutral or positive about dating someone with a psychiatric history, while 27% (7/26) expressed reluctance.

Interviews

Thematic analysis was used to identify patterns and themes from participants' postconsultation interviews. A thematic map summarizing the relationships among the identified themes is presented in Figure 2.

Figure 2. Thematic map of participants' experiences with metaverse-based psychiatric consultations (N=26) conducted at Yokohama City University Hospital between July 2023 and November 2023. The map illustrates the relationships among the key themes identified through thematic analysis of postconsultation interviews: usability of the metaverse device, acceptance of metaverse consultations, and contexts in which metaverse consultations may be particularly beneficial for young people with mental health conditions.



Usability of the Metaverse Device

Participants expressed a range of views regarding usability. Approximately 46% reported positive experiences, describing the device as intuitive or comparable to gaming interfaces. About 23% expressed neutral views, noting that while manageable for short sessions, prolonged use might be physically demanding. In contrast, 31% reported negative experiences, primarily related to physical discomfort, device fit, or technical complexity.

Participants who reported positive experiences noted that they "quickly got used to the controls" (Participant 10, 19, 20), and found the device "easy to use due to regular use of gaming devices" (Participant 9, 13, 16, 22). Optimism for future accessibility was evident in comments such as "I would like to use it when it becomes easier" (Participant 4) and "more affordable" (Participant 23, 24).

Participants with neutral views indicated that although they adapted to the operations, more complex tasks might require assistance. One participant commented,

> *I feel comfortable for short sessions, but longer sessions might be tough with these devices.* [Participant 4]

Those expressing negative views raised concerns about the device's physical fit and comfort. Nine participants experienced issues such as the goggles feeling "too tight" (Participant 18), "too loose and slipping" (Participant 13, 14), or challenging to fit over glasses. Five participants reported mild physical discomfort, including VR-related discomfort or head heaviness, although no psychological discomfort was noted. A participant remarked, "It might be difficult to connect and operate remotely without staff assistance" (Participant 18), highlighting barriers to independent use.

Acceptance of the Metaverse Consultation

Responses regarding the acceptance of metaverse consultations revealed a range of perspectives.

Thirty-eight percent of participants expressed a preference for metaverse consultations over face-to-face sessions, citing benefits such as reduced psychological pressure and convenience. The comments included, "It's a big help not having to leave home when I'm feeling too unwell to go out"

(Participant 12) and "Meeting a new doctor is less nerve-wracking through an avatar" (Participant 3). Another participant noted,

> *I don't have to endure the intimidating atmosphere of psychiatric institutions or the doctor's imposing presence.* [Participant 19]

Another 38% of participants expressed neutral responses, describing the content and quality of metaverse consultations as comparable to face-to-face consultations. Many noted that their preference would depend on their condition at the time. For example, one participant remarked,

> *I prefer face-to-face if I can go out, but there are times I'd rather use the metaverse.* [Participant 18]

Others suggested that

> *The metaverse would be preferable if issues such as cost, ease of access, and privacy were addressed.* [Participant 24]

The remaining 24% preferred face-to-face consultations, emphasizing the reassurance of observing facial expressions and body language. One participant shared,

> *If I can't see their face, I worry whether they're truly understanding or accurately interpreting what I want to convey.* [Participant 4]

Another added,

> *For personal and serious discussions, I want to see the person face-to-face.* [Participant 8]

Participants also shared insights into specific scenarios where metaverse consultations might be beneficial. One participant stated,

> *It's ideal for people like me who are self-conscious about being seen. I can focus more on the consultation and express what I truly want to say.* [Participant 9]

Another remarked,

> *It's helpful for those who find it challenging to visit psychiatric clinics.* [Participant 1]

Keywords and Concerns for Metaverse Consultations

Participants highlighted several key requirements and concerns regarding implementation. Security and privacy were frequently emphasized, particularly the need for a secure and private consultation environment. The participants requested assurances that psychiatrists understood them accurately. One participant commented,

> *I don't want to show my face, but if the avatar's facial expressions and body movements are synchronized with reality, it feels more reassuring than a phone call.* [Participant 1]

Concerns about information security for private consultations were also raised.

Customizability of avatars and virtual spaces was another recurring theme. Participants frequently emphasized the importance of customizable settings, using terms such as "relaxing," "free from distractions," and "self-selectable." Twelve participants expressed a preference for avatars that felt authentic to them, with one stating,

> *choosing my avatar is a way of expressing myself, and it makes me feel more comfortable in the consultation.* [Participant 10]

Preferences for human avatars (6 participants) and nonhuman characters (6 participants) were evenly split.

Psychiatric Team's Perspective

The psychiatric team provided valuable insights into the potential benefits and challenges of metaverse consultations.

Team members noted that individuals with sensory hypersensitivity, such as those with traits associated with autism spectrum disorder, appeared to focus more effectively in the immersive VR environment. They also reported that individuals with significant social anxiety or tension seemed to relax more quickly, enabling broader and deeper conversations.

At the same time, concerns were raised regarding the suitability of metaverse consultations for participants with pronounced symptoms, as certain clinical cues may be less observable in virtual settings. Suggestions included simplifying metaverse operations for easier access and expanding the range of avatars and room settings to allow for more personalized consultations. They also recommended developing diagnostic support tools to enhance the consultation experience.

Discussion

Principal Findings

This study evaluated the feasibility and user experience of metaverse-based psychiatric consultations for young people with mental health conditions. The findings demonstrated that, in this study, such consultations are technically feasible and safe, with no major adverse events. Participants reported high levels of engagement, and their postexperience feedback highlighted the unique advantages of avatar-mediated interaction. While some physical discomfort was noted, the overall acceptance of metaverse consultations suggests their potential as a complementary modality in youth mental health care.

Interpretations of Findings

Our results identified specific groups of young people who showed a strong affinity for metaverse consultations, including those with social anxiety, sensory sensitivities (eg, autistic traits), difficulty leaving home due to mental illness, concerns about stigma, and discomfort with their physical appearance. For these individuals, avatar-based interaction lowered psychological barriers and provided a sense of safety and autonomy. These findings are consistent with existing literature showing that digital interventions can enhance help-seeking among youth when designed to offer privacy, flexibility, and user control [9,15,20].

The immersive VR environment was particularly appreciated by participants with sensory sensitivities, as one participant remarked,

> *After experiencing the metaverse consultation, I felt I truly understood what a consultation was meant to be for the first time.* [Participant 2]

This finding may be interpreted through the lens of presence theory, which suggests that immersive environments can enhance users' sense of "being there," potentially facilitating emotional engagement and attentional focus [23].

The ability to interact through avatars in a spatialized environment may also support a form of digital embodiment, enabling participants to regulate interpersonal distance and self-presentation more flexibly than in face-to-face or video-based consultations. This capacity to modulate proximity and representation aligns with findings from embodiment research, which suggest that virtual body ownership and perspective-taking can influence affective and social responses [24]. Such mechanisms may partially explain why some participants reported feeling more relaxed and able to engage in deeper conversations within the metaverse setting.

On the other hand, previous studies caution that VR may also induce discomfort in some individuals with autism spectrum disorder [24]. This duality highlights the need for individualized approaches and flexible options.

In terms of accessibility, our findings revealed operational challenges such as the need for technical support, device heaviness, and VR-related discomfort. These barriers align with broader concerns regarding the digital divide and unequal access to advanced immersive technologies, particularly among young people with mental health conditions. Previous research has demonstrated that individuals with mental ill health, including socioeconomically and digitally marginalized youth, may be limited or nonusers of digital interventions despite device access, suggesting that skills, motivation, and confidence can constitute significant barriers to digital engagement [25,26]. Access to high-end VR hardware may require financial, technological, and spatial resources that are not evenly distributed, potentially exacerbating existing disparities in MHS utilization.

From a technology acceptance perspective, perceived ease of use and perceived usefulness are central determinants of user adoption in health technologies [26]. When devices are physically uncomfortable or operationally complex, perceived ease of use may decline, thereby reducing users' willingness to engage with the platform. Therefore, simplifying hardware requirements and offering lighter, cross-platform alternatives may be essential to ensure equitable and scalable implementation of metaverse-based MHSs. This underscores the importance of exploring less resource-intensive alternatives, such as "light metaverse" platforms that are accessible via widely available devices, including smartphones or personal computers. Expanding metaverse options beyond VR goggles could help reach a wider population and improve inclusivity [18].

In interpreting these findings, it is also important to situate metaverse-based consultations in relation to existing digital mental health modalities, particularly video-based teleconferencing, which is currently the most widely used form of telepsychiatry. Teleconferencing has demonstrated effectiveness in increasing access to care and reducing geographical barriers [27,28]. However, because it typically relies on real-time videoconferencing, it retains key interpersonal elements of face-to-face encounters (eg, visual and vocal cues, facial interaction, and eye contact), while also introducing heightened self-presentation and appearance-related attentional demands [29]. In contrast, metaverse-based consultations have been proposed to offer distinct experiential affordances through avatar-mediated interaction and immersive environments [18]. For some participants, these features appeared to reduce psychological barriers associated with being seen, judged, or scrutinized, thereby facilitating disclosure and engagement. At the same time, the use of VR technology introduced additional usability burdens, including physical discomfort, device complexity, and the need for technical support, which are less prominent in conventional teleconferencing. These findings suggest that metaverse-based consultations should not be viewed as a replacement for teleconferencing, but rather as a complementary modality that may be particularly valuable for specific subgroups of young people for whom video-based interaction remains challenging. Future research directly comparing immersive metaverse approaches with standard teleconferencing is needed to clarify relative advantages, limitations, and appropriate indications within stepped or hybrid models of youth mental health care.

Participants also emphasized the value of choice in how they receive mental health support. The concept of choice emerged consistently in participants' responses, highlighting their desire for flexibility and personalization. The ability to choose avatars and participate in consultations from private spaces fostered a greater sense of agency. This aligns with prior research emphasizing the importance of autonomy and co-designed services in engaging youth with mental health needs [6,17,30,31].

Ethical challenges remain. While our study obtained consent in person, widespread adoption of metaverse consultations will require mechanisms to ensure informed consent, protect privacy, and uphold safety in fully virtual settings [32]. Addressing these ethical and operational hurdles is essential for translating the potential of virtual environments into sustainable clinical practice.

Strengths and Limitations

Strengths

This is the first observational trial to explore the feasibility of psychiatric consultations in a metaverse setting, offering novel insights into how digital environments can be leveraged to support youth mental health. The study benefited from a youth-centered design, the involvement of experienced psychiatrists, and the incorporation of diverse participant feedback. This design enabled a nuanced understanding of how metaverse-based consultations may meet the psychological and logistical needs of underserved youth populations, including those with interpersonal anxiety, sensory sensitivities, or barriers to in-person care.

Limitations

Several limitations should be noted. First, the sample size was modest, and participants were primarily recruited from urban

or institutional settings, which may limit the generalizability of the findings to broader or more diverse populations. Second, the study focused solely on avatar-based communication within VR platforms, without evaluating broader features of the metaverse, such as social engagement spaces, gamified environments, or decentralized user governance structures such as DAOs. Third, populations such as nonnative speakers or individuals with speech impairments were not included, which may limit the inclusivity of the findings. Future studies should explore comparative modalities (eg, light vs heavy metaverse), include more diverse participants, and assess additional functional elements of digital environments to further understand the potential of metaverse-based mental health support.

Implications and Conclusions

This study provides early evidence that metaverse-based psychiatric consultations are a feasible and acceptable approach for supporting young people with mental health conditions. The innovation of this study lies in its focus on avatar-mediated psychiatric consultation within a metaverse environment, moving beyond conventional telepsychiatry models by examining how immersive, customizable virtual spaces may influence user experience and engagement. Unlike prior digital mental health studies that primarily evaluate video- or text-based teleconferencing, this study highlights the distinct role of immersive and self-representational features—such as avatars and virtual environments—in potentially reducing psychological barriers, enhancing autonomy, and supporting help-seeking among youth who experience anxiety, stigma, or discomfort with face-to-face care. By identifying specific subgroups of youth for whom metaverse-based consultations may be particularly beneficial, this study contributes to the emerging field of youth digital mental health by offering practical insights into when and for whom immersive technologies may add value beyond existing modalities.

From a real-world perspective, metaverse-based psychiatric consultations may serve as a complementary access point within stepped or hybrid care models, particularly for young people who face psychological or logistical barriers to in-person or video-based services. However, careful consideration of usability, digital equity, and ethical safeguards will be essential to ensure responsible and scalable implementation. Future research should compare immersive metaverse approaches with conventional teleconferencing, examine long-term clinical outcomes, and explore scalable implementation strategies to support equitable and youth-centered mental health care across diverse settings.

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Data Availability

The datasets generated and analyzed during this study are not publicly available due to ethical restrictions and the sensitive nature of the participants' mental health information. Requests for access to the deidentified data can be directed to the corresponding author and may be considered on a case-by-case basis, subject to institutional review board approval. The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Conceptualization: MI, JF, NT, KI, T Moroga, T Miyazaki
Data curation: NT, T Moroga, MT
Formal analysis: MI, JF, NT
Funding acquisition: MI
Investigation: MI, JF, NT, KI, T Moroga, MT, TA
Methodology: MI, JF, KI
Project administration: MI, T Miyazaki
Resources: T Moroga, MT, T Miyazaki
Supervision: TA, T Miyazaki
Writing – original draft: MI, JF
Writing – review & editing: MI, JF, NT, KI, T Moroga, MT, TA, T Miyazaki

Conflicts of Interest

MI, NT, KI, TM, MT, TA, and TM declare no competing interests. JF serves as the Executive Director of the Seisa Yokohama Education Counselling Center.

Multimedia Appendix 1
Interview guide that is used for semistructured interview for participants.
[PDF File, 27 KB - xr_v3i1e83688_app1.pdf]

Checklist 1
COREQ checklist.
[PDF File, 61 KB - xr_v3i1e83688_app2.pdf]

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Abbreviations

COREQ: Consolidated Criteria for Reporting Qualitative Research
ICT: information and communication technology
MHS: mental health service
VR: virtual reality

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Perceived Usability, User Experience, and Technology Acceptance of Role-Specific Augmented Reality Decision Support Tools for Cardiac Arrest Resuscitation: Prospective Observational Pilot Study

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Abstract

Background: Cardiac arrest is a critical medical emergency that requires strict adherence to clinical guidelines to achieve optimal outcomes. Deviations from these guidelines, often due to task complexity, can adversely affect patient outcomes. Augmented reality (AR) offers a way to deliver role-specific, in-view guidance, but evidence on its perceived usability, user experience, and acceptability in cardiac arrest resuscitation remains limited.

Objective: This study aimed to design, develop, and evaluate a role-specific AR decision support system for resuscitation team leaders and medication nurses. In this observational study, we assessed clinicians' perceived usability, user experience, and technology acceptance of the new AR system in a high-fidelity simulated cardiac arrest scenario.

Methods: We conducted a prospective observational pilot study using a high-fidelity simulated pediatric cardiac arrest scenario. A total of 10 clinicians were recruited from Alberta Children's Hospital, including 5 (50%) of 10 pediatric emergency physicians serving as team leaders (men: 3/5, 60%, and women: 2/5, 40%; median age 41, IQR: 40-42 y) and 5 (50%) of 10 emergency nurses serving as medication nurses (men: 1/5, 20%, and women: 4/5, 80%; median age 45, IQR: 42-46 y). Participants used role-specific AR decision support interfaces deployed on HoloLens 2 head-mounted displays. Following the simulation, perceived usability, user experience, and technology acceptance were assessed using validated questionnaires: the System Usability Scale, User Experience Questionnaire, and Technology Acceptance Model. Data were collected via postsimulation surveys and analyzed descriptively.

Results: Descriptive analyses were performed without inferential statistical testing. The mean System Usability Scale scores were 75.5 (SD 9.25, 95% CI 64.0 - 87.0) for team leaders and 82.0 (SD 11.20, 95% CI 68.0 - 96.0) for medication nurses. User experience was positive across roles, with mean User Experience Questionnaire scores indicating favorable attractiveness (team leaders: 1.87, SD 1.14, 95% CI 0.45 - 3.28; medication nurses: 2.43, SD 0.52, 95% CI 1.79 - 3.08), pragmatic quality (team leaders: 1.88, SD 0.87, 95% CI 0.80 - 2.97; medication nurses: 1.80, SD 0.69, 95% CI 0.94 - 2.66), and hedonic quality (team leaders: 2.40, SD 0.89, 95% CI 1.30 - 3.50; medication nurses: 2.28, SD 0.69, 95% CI 1.42 - 3.13). Technology acceptance was high, with mean combined Technology Acceptance Model scores of 5.92 (SD 0.46, 95% CI 5.35 - 6.49) for team leaders and 6.02 (SD 0.56, 95% CI 5.32 - 6.71) for medication nurses.

Conclusions: This study introduces a novel role-specific AR decision support system that delivers tailored, in-view guidance to resuscitation team leaders and medication nurses during cardiac arrest. Unlike prior cognitive aids that present uniform or device-agnostic information, this system explicitly adapts interface content and structure to distinct clinical roles and workflows. The findings contribute early empirical evidence on the perceived usability, user experience, and acceptability of role-tailored

AR support in high-acuity team settings and yield transferable design principles for developing role-aware AR interfaces. In real-world contexts, such systems may support protocol adherence and team coordination during resuscitation training and early-stage clinical deployment, informing future evaluations that incorporate objective performance and workflow outcomes.

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KEYWORDS

cardiopulmonary resuscitation; augmented reality; simulation training; wearable electronic devices; digital health; user-computer interface; decision support systems; clinical guideline adherence; technology acceptance; user-centered design

Introduction

Cardiopulmonary resuscitation (CPR) is administered to thousands of patients experiencing cardiac arrests (CAs) each year in North America [1]. Guideline-compliant basic life support and advanced life support guidelines significantly improve patient outcomes following CA [2,3]. However, health care providers often face challenges in consistently adhering to these guidelines during in-hospital CA events. Deviations, such as delays in epinephrine administration, defibrillation, and medication dosing errors, are commonly linked to poor patient outcomes [4]. These deviations are often attributed to the high cognitive demands and mental workload experienced by resuscitation team members [5,6].

Cognitive aids, designed to assist in decision-making and information recall, have demonstrated improved adherence to resuscitation guidelines during simulated cardiopulmonary arrest events [7-11]. By reducing errors and improving the timing of key interventions, cognitive aids can enhance clinical performance [12]. However, traditional cognitive aids, such as pocket cards, sometimes introduce delays in initiating CPR or administering drugs due to their design limitations or complexity, highlighting the need for more efficient, role-specific decision-support solutions. Recent scoping and systematic reviews published in the past few years highlight a growing interest in immersive technologies, including augmented reality (AR), for resuscitation training and emergency care, while also identifying variability in system design, evaluation approaches, and integration with clinical workflows [13,14].

AR overlays digital content onto the physical environment, enabling real-time delivery of context- and role-specific prompts directly in the user's field of view [15]. AR systems have been explored in CPR and emergency care training contexts, with some evidence of improved engagement and task performance compared with conventional approaches, although results remain heterogeneous and context-dependent [16,17]. Previous AR-based work in resuscitation and safety-critical domains further suggests that spatially registered visual cues can support situational awareness and reduce reliance on external reference materials during time-sensitive tasks [15,18,19]. Despite this growing body of work, recent reviews emphasize that evidence regarding the usability, user experience, and acceptability of wearable AR systems in CA resuscitation—particularly from the perspective of end users—remains limited [13,14].

To address these gaps, this study presents the design, development, and formative evaluation of an AR-based decision support system tailored to the resuscitation team leader (physician) and medication nurse roles during CA resuscitation. The objectives of this study were to (1) describe how team leaders and medication nurses perceive the AR system's usability and user experience when used during a simulated resuscitation scenario and (2) describe how team leaders and medication nurses perceive the system's acceptability and its potential for future integration into clinical practice.

Methods

Ethical Considerations

Ethics approval was obtained from the University of Calgary (REB23-1007) and the University of Geneva Health Research Ethics Boards (Req-2023 - 00162). Before participation, all participants were provided with written information describing the study purpose, procedures, potential risks, and data handling practices, and written informed consent was obtained. Participation was voluntary, and participants were informed that they could withdraw from the study at any time without consequence. Consent included permission to collect survey data and to use nonidentifiable data and images generated during the simulation for research and publication purposes. Privacy and confidentiality were ensured for all study participants. No images included in the manuscript or supplementary materials contain identifiable information about individual participants. Participants did not receive any compensation for their role in this study.

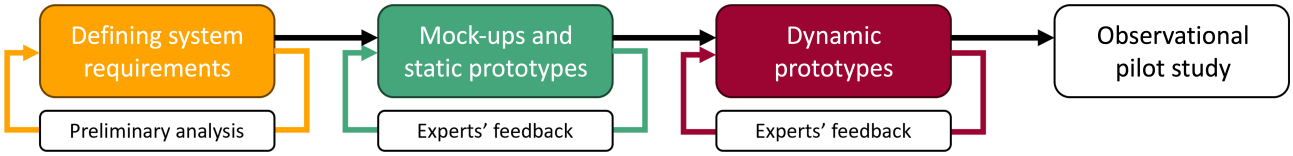
Study Design: Experimental Setting

This study was designed as a prospective observational pilot study conducted in a high-fidelity pediatric CA simulation setting. The following section describes the overall process of the AR system design and development, which was used in the study.

Iterative Design and Development Process of the AR System

For our study, role-specific AR decision support systems for team leaders (physicians) and medication nurses were developed following a 4-phase, iterative prototyping process grounded in user-centered and clinician-informed design practices (Figure 1). Phases 1 to 3 focused on system design and development, whereas phase 4 evaluated the final prototype in a simulation-based clinical environment through an observational pilot study. The objective of this process was to progressively refine AR design concepts into a stable, simulation-ready system through iterative feedback and close collaboration with clinical domain experts.

Figure 1. Four-phase iterative development process.



Phase 1: Defining System Requirements

This phase focused on identifying the clinical, informational, and workflow requirements necessary to guide the content and design of the role-specific AR interfaces. A total of 30 health care professionals (15, 50%, emergency physicians and 15, 50%, emergency nurses) from Alberta Children's Hospital (ACH) and Geneva University Hospitals were surveyed to assess preferences for role-specific information, AR layout components, timer placement and behavior, and medication-related display features. Clinicians viewed role-specific, task-focused information as important elements of the AR system. Both physicians and nurses emphasized the utility of receiving targeted, step-relevant prompts through the AR headset. Real-time updates regarding current and upcoming tasks ("next steps") were perceived to enhance workflow by reducing the need to reference external materials visually. Both groups rated time-based cues highly, with the integration of a CPR timer (for the team leader) and an epinephrine timer (for the team leader and medication nurse) described as highly important for the AR headset. A detailed list of resuscitation medications and associated dosages was also rated highly for both groups of providers. Physicians expressed the desire to be notified when medications were given. These insights directly informed the layout, information hierarchy, and alerting behavior of the static (phase 2) and dynamic (phase 3) prototypes, ensuring that the AR interface design aligned with clinicians' informational needs and workflow demands. Table 1 provides a summary of key insights from phase 1.

Table . Key insights from each phase of the iterative development process.

Phase	Key insights
Phase 1: Defining system requirements	• Role-specific, task-focused clinical prompts • Current tasks (prioritized) • Next steps (prioritized) • CPR[a] timer (team leader) • Epinephrine timer (team leader and medication nurse) • Medication reference • Medication given—notification for team leader
Phase 2: Mock-ups and static prototypes	• Interface separation by user role improves clarity and relevance of displayed information. • Visually simple, structured layouts are preferred for rapid information recognition. • Timers and other time-sensitive elements should be placed in the upper peripheral field of view to avoid obstructing the patient. • Current tasks should be listed on the left and next steps to the right. • Cardiac rhythm should be displayed in the physician's augmented reality headset. • Patient weight should be displayed on the medication nurse display. • Other UI[b] elements should be fixed in space (e.g., clinical algorithm, Hs and Ts, medication reference) to avoid interference when team members move through the field of view.
Phase 3: Dynamic prototype	• Functional CPR and epinephrine timers included escalating visual cues. • The UI was visually refined with higher contrast, low-profile components, reorganized medication content, and larger fonts. • Medication card (team leader): categorized drug details with interactive dose counters • Guideline algorithm panel (team leader): full cardiac arrest algorithm visualization with a stage-tracking arrow. • Hs and Ts reference (team leader): a structured list of reversible causes for rapid diagnostic review. • Medication card (medication nurse): categorized drugs with strength, dose, volume, and instructions, plus an interactive syringe counter for tracking prepared or administered doses. • UI elements were arranged to maximize visibility and minimize occlusion during dynamic resuscitation.

[a]CPR: cardiopulmonary resuscitation.

[b]UI: user interface.

Phase 2: Mock-Ups and Static Prototypes

In this phase, the requirements identified in phase 1 were transformed into static prototype designs. Initial mock-ups were created to visualize the AR layout, role-specific information elements, and overall display functionality. To optimize role-specific design, separate static layouts were developed for the team leader and medication nurse roles. The team leader interface focused on 4 key elements (i.e., the CPR timer, epinephrine timer, current task list, and next task list), whereas the medication nurse interface incorporated 3 core elements (i.e., epinephrine timer, current task list, and next task list). A total of 9 static prototypes were created for the team leader, and 5 prototypes were created for the medication nurse, exploring variations in spatial arrangement and visual hierarchy (Figures S1 and S2 in Multimedia Appendix 1).

In total, 5 emergency room physicians and 5 emergency room nurses from ACH were selected to provide feedback on static layouts for their corresponding profession. Participants were shown each static layout in sequence and asked to provide verbal feedback regarding spatial organization, information grouping, font and icon size, color and contrast of user interface (UI) elements, and the position of UI elements relative to equipment and providers in the clinical space. Physicians rated their top 3 display options, and nurses were asked to rate their top 2 options. Feedback was documented using annotated screenshots and meeting notes. On the basis of this feedback, 3 dynamic prototypes for the team leader and 2 dynamic prototypes for the medication nurse were developed to ensure that UI elements were easy to identify, accessible, and minimally intrusive within the AR field of view. Table 1 provides a summary of key insights from phase 2.

Phase 3: Dynamic Prototypes

This phase involved developing and iteratively refining dynamic AR prototypes for both the team leader and medication nurse roles. Dynamic interface layouts were implemented using Unity and deployed on the Microsoft HoloLens 2. The initial dynamic versions preserved the core components established during the static prototyping phase, while introducing functional timers,

refined visual elements, and interactive components. For the medication nurse interface, an adjustable epinephrine dose counter was implemented, allowing users to adjust the number of doses prepared or administered. To guide iterative refinement, the 10 participants from phase 2 returned to provide feedback on the dynamic prototypes. Participants were asked to evaluate layout preferences, timer behavior, visual clarity, and ease of interaction. Additional role-specific questions were directed to team leaders and medication nurses to capture feedback aligned with each role's clinical responsibilities.

Feedback sessions identified refinements to visual hierarchy, timer behavior, text sizing, and the placement of role-specific components. Experts also evaluated the positioning of fixed elements such as the CA algorithms, reversible causes (Hs and Ts), and the medication card, providing insight into potential visual obstruction during active resuscitation. Feedback informed key improvements to support clarity, usability, and workflow alignment. Functional CPR and epinephrine timers were revised to include escalating visual cues (yellow flash at 10 s and rapid red flash at 1 s). The UI was visually refined with higher contrast, low-profile components, reorganized medication content, and larger fonts. An interactive epinephrine dose counter was added for medication nurses. Participants also emphasized the need to reposition or hide large reference panels to prevent obstruction and maintain clear grouping of current and upcoming tasks. Table 1 provides a summary of key insights from phase 3. All recommended changes were incorporated into one final updated dynamic prototype for the team leader (Figure 2) and medication nurse (Figure 3).

Figure 2. Team leader display showcasing real-time CPR and medication timers, visual alerts for task progression, and stepwise guidance for current and upcoming guideline tasks during a simulated cardiac arrest (CA) scenario. When in use, the CA algorithm, reversible causes, and medication card are positioned out of view when the team leader is looking straight ahead. To view each of these items, the team leader must turn to the left (to see the algorithm), to the right (to see the reversible causes), or look slightly down (to see the medication card). CPR: cardiopulmonary resuscitation; PEA: pulseless electrical activity; pVT: pulseless ventricular tachycardia; ROSC: return of spontaneous circulation; TEP: Treatment Escalation Plan; VF: ventricular fibrillation.

Figure 3. Medication nurse display showing step-by-step guidance on drug dosages, preparations, and administration timing, with a real-time epinephrine timer for ensuring timely interventions.

Final System Architecture and Components

The AR system used in this study was developed using a server-client architecture to enable seamless, real-time synchronization between a web-based control system operated by the experimenter and the role-specific AR interfaces used by the team leader and medication nurse (Figure S3 in Multimedia Appendix 1). This architecture ensured that each user received only the information relevant to their role while maintaining consistent timing, event updates, and algorithm progression across devices.

- Web-based control system (server): A centralized web-based control system was implemented to manage scenario flow and synchronize data to both AR devices (Figure S4 in Multimedia Appendix 1). During the simulation, the experimenter used this interface to advance the CA algorithm, trigger event notifications, reset timers, and record medication administration (Figure S5 in Multimedia Appendix 1). All adjustments made on the server were immediately transmitted to the AR clients, enabling real-time display without perceptible delay.
- AR interfaces for team leader and medication nurse (client): Two separate AR client applications were deployed on the HoloLens 2 devices, one for each role. These interfaces displayed synchronized timers, role-specific prompts, algorithm guidance, medication information, and interactive elements (e.g., dose counters). The client applications integrated incremental refinements derived from clinician feedback during dynamic prototyping, ensuring that the displays aligned with each role's workflow and cognitive demands.

Together, the server-client architecture, real-time synchronization, and role-specific display features formed a cohesive system for supporting resuscitation team members during high-acuity pediatric CA scenarios.

Phase 4: Simulation-Based System Evaluation

Phase 4 consisted of a prospective, observational pilot study in which participants managed a simulated CA scenario using the final prototype of the AR system.

Participants and Sample Size

Participants were recruited from the pediatric emergency department at ACH. All participants had completed basic life support and pediatric advanced life support training. There were no specific exclusion criteria. A convenience sample of 10 health care professionals participated, consisting of 5 (50%) pediatric emergency physicians (team leaders) and 5 (50%) emergency nurses (medication nurses). The same 10 participants who provided feedback in phases 2 and 3 were paired into physician-nurse dyads, with each clinician assigned the AR interface corresponding to their respective profession.

Study Procedure: Simulated CA Scenario

The simulation scenarios took place in the KidSIM Pediatric Simulation Center at ACH using a high-fidelity pediatric manikin (Laerdal SimJunior). Each dyad (1 physician team leader and 1 medication nurse) was embedded within a larger clinical resuscitation team composed of 3 additional research actors playing the roles of airway provider, bedside clinician, and CPR provider to recreate an authentic team-based resuscitation environment. The 2 study participants wore HoloLens 2 devices displaying their respective role-specific AR interfaces.

The scenario simulated an in-hospital pediatric CA involving a 5-year-old boy who presented with pulseless ventricular tachycardia, progressing through ventricular fibrillation and

pulseless electrical activity, before achieving return of spontaneous circulation at the 18-minute mark. Participants, acting as team leader or medication nurse, were guided by visual prompts on their respective AR displays. The team leader guided overall clinical management, including airway management, CPR, defibrillation, and ordering medications. The medication nurse handled medication preparation and administration, following role-specific cues on the AR interface. Research actors were trained to function in their role as they would in a real CA.

Measures

To provide a comprehensive assessment of the AR support system's perceived usability, user experience, and acceptance, we used 3 well-established instruments. The System Usability Scale (SUS) was used to measure perceived usability. It consists of 10 statements that assess users' perceptions of system ease of use and overall usability [20,21]. Each statement is rated on a 5-point Likert scale, ranging from "strongly disagree" (1) to "strongly agree" (5), capturing both ease of use and learnability. SUS scores are calculated by first adjusting responses: for odd-numbered items, 1 is subtracted from the user's rating, and for even-numbered items, the rating is subtracted from 5. The adjusted scores for each statement are summed, and the total is multiplied by 2.5 to convert the raw score to a range of 0 to 100. On the basis of empirical benchmarks reported by Bangor et al. [21], SUS scores above 68 are generally interpreted as above average, whereas scores around 80 or higher are commonly associated with excellent usability. These benchmarks provide a practical reference for interpreting system usability levels. The SUS has demonstrated strong psychometric properties across diverse systems and application domains, including high internal consistency and established construct validity. Prior validation studies have shown that SUS scores are robust and interpretable even in small-sample usability evaluations, making the instrument suitable for early-stage and pilot studies [20,21].

The User Experience Questionnaire (UEQ) evaluates multiple dimensions of perceived user experience, including *attractiveness*, *pragmatic quality*, and *hedonic quality* [22]. The UEQ consists of 26 items rated on a 7-point semantic differential scale ranging from −3 (most negative) to +3 (most positive), capturing users' subjective impressions of different aspects of system interaction.

- Attractiveness: reflects the overall appeal of the system and represents users' general impression.
- Pragmatic quality: captures perceived task-oriented aspects of the system use, focusing on how well users feel the system supports task accomplishment through three subdimensions: (1) perspicuity: ease of understanding and familiarization, (2) efficiency: perceived smoothness and effort associated with task execution, and (3) dependability: user's perceived sense of control and predictability during interaction.
- Hedonic quality: captures the emotional and experiential aspects of interaction, covering (1) stimulation: how engaging and motivating the system feels; and (2) novelty: perceived originality and creativity of the system.

UEQ scale values above 0.8 are commonly interpreted as indicating a positive experience, whereas higher values may be classified as above average or excellent when compared against UEQ benchmark distributions, depending on the specific scale [23,24]. By distinguishing between pragmatic and hedonic qualities, the UEQ provides insight into both task-oriented interaction perceptions and experiential aspects of system use. The distinction is particularly relevant for AR systems, where perceived interaction support and user engagement jointly shape overall user experience. Validation studies of the UEQ have demonstrated acceptable to good internal consistency across its subscales and established construct validity for distinguishing between pragmatic and hedonic dimensions of user experience across a wide range of interactive systems [22-24].

The Technology Acceptance Model (TAM) assesses user acceptance of new technologies based on the relationship between two main dimensions: (1) perceived usefulness (PU), which measures the extent to which users believe that using a given technology enhances their job performance; and (2) perceived ease of use (PEU), which evaluates the extent to which users believe that using a technology will result in less effort to perform their tasks, focusing on its intuitiveness and the learning curve involved [25]. For this study, TAM was adapted to include 12 items across 2 primary dimensions, each rated on a 7-point Likert scale, ranging from "strongly disagree" (1) to "strongly agree" (7). Scores are averaged for each dimension. High scores across both dimensions suggest that users view the system as both beneficial and user-friendly—key factors for ensuring sustained use [26]. The PU and PEU constructs within TAM have demonstrated strong reliability and predictive validity for technology adoption and use intention across numerous information systems and health care technology studies, supporting their use in evaluating acceptance of emerging technologies, such as AR [25,26].

Statistical Analysis

In this observational pilot study, there were no missing data for survey responses, and all analyses were descriptive in nature and aimed at characterizing perceived usability, user experience, and technology acceptance of the AR system across clinical roles. For each outcome measure, summary statistics were computed separately for the team leader and medication nurse roles. For the SUS, UEQ, and TAM measures, central tendency and variability were summarized using means and SDs. SEs and 95% CIs for the mean were calculated to indicate the precision of the estimates. Where appropriate, medians and IQRs were visualized using box plots to illustrate score distributions.

Given the small sample size and the exploratory nature of this pilot evaluation, no formal hypothesis testing or inferential comparisons between roles were performed. Instead, overlapping CIs were used to support cautious interpretation of observed differences, consistent with recommendations for early-stage usability and feasibility studies.

Results

Participant Demographics

A total of 10 health care professionals participated in the study, comprising 5 (50%) pediatric emergency physicians (team

leaders) and 5 (50%) emergency nurses (medication nurses). Participants varied in age and clinical experience, with medication nurses generally reporting longer durations of practice and greater exposure to CA events. Most participants had limited prior experience with AR technologies, particularly in professional clinical contexts. Table 2 provides an overview of the participants' demographic characteristics.

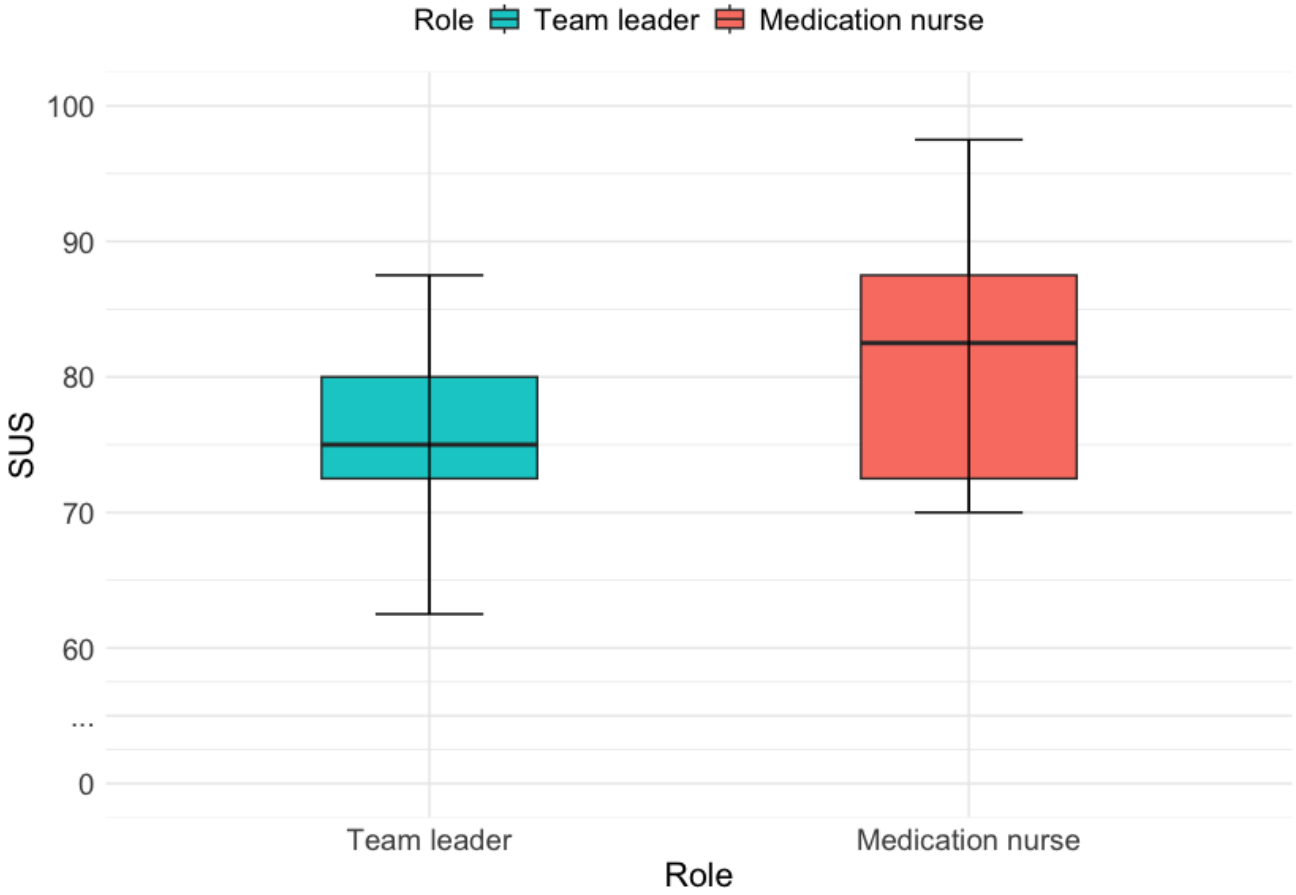
Table . Participant demographics.

	Team leader (n=5)	Medication nurse (n=5)
Gender, n (%)		
Male	3 (60)	1 (20)
Female	2 (40)	4 (80)
Age (y), median (IQR)	41 (40 - 42)	45 (42 - 46)
Duration in practice (y), median (IQR)	12 (11 - 13)	20.5 (17 - 24.25)
How many times have you had to care for a child in cardiac arrest during a *real, live event* in the past 2 y?, median (IQR)	1 (1 - 4)	2 (2 - 3)
How many times have you had to care for a child in cardiac arrest during a *simulated event* in the past 2 y?, median (IQR)	4 (2 - 4)	5 (4 - 6)
Have you ever used any type of augmented reality device for *professional use*?	1 participant with prior experience (>10 times)	No prior experience
Have you ever used any type of augmented reality device for *recreational use* (e.g., gaming)?	3 participants (>10 times)	1 participant (1 - 4 times)

Perceived Usability

The AR system demonstrated favorable perceived usability for both roles (Figure 4); however, the precision of these estimates varied across roles. The SUS revealed that the team leader role scored a mean of 75.50 (SD 9.25, SE 4.14, 95% CI 64.00-87.00), corresponding to a "B" grade (74.10 - 77.10) on the SUS grading scale, categorized as "good" (Multimedia Appendix 2). The score generally suggests that team leaders perceived the system as usable and user-friendly; however, the relatively wide CI reflects uncertainty associated with the small sample size and indicates that this estimate should be interpreted cautiously.

Figure 4. Box plot displaying System Usability Scale (SUS) scores for the team leader and medication nurse roles using the augmented reality support system. Higher median SUS scores for medication nurses indicate greater ease of interaction and workflow support, reflecting an "excellent" grade compared to the "good" usability rating for the team leader role.



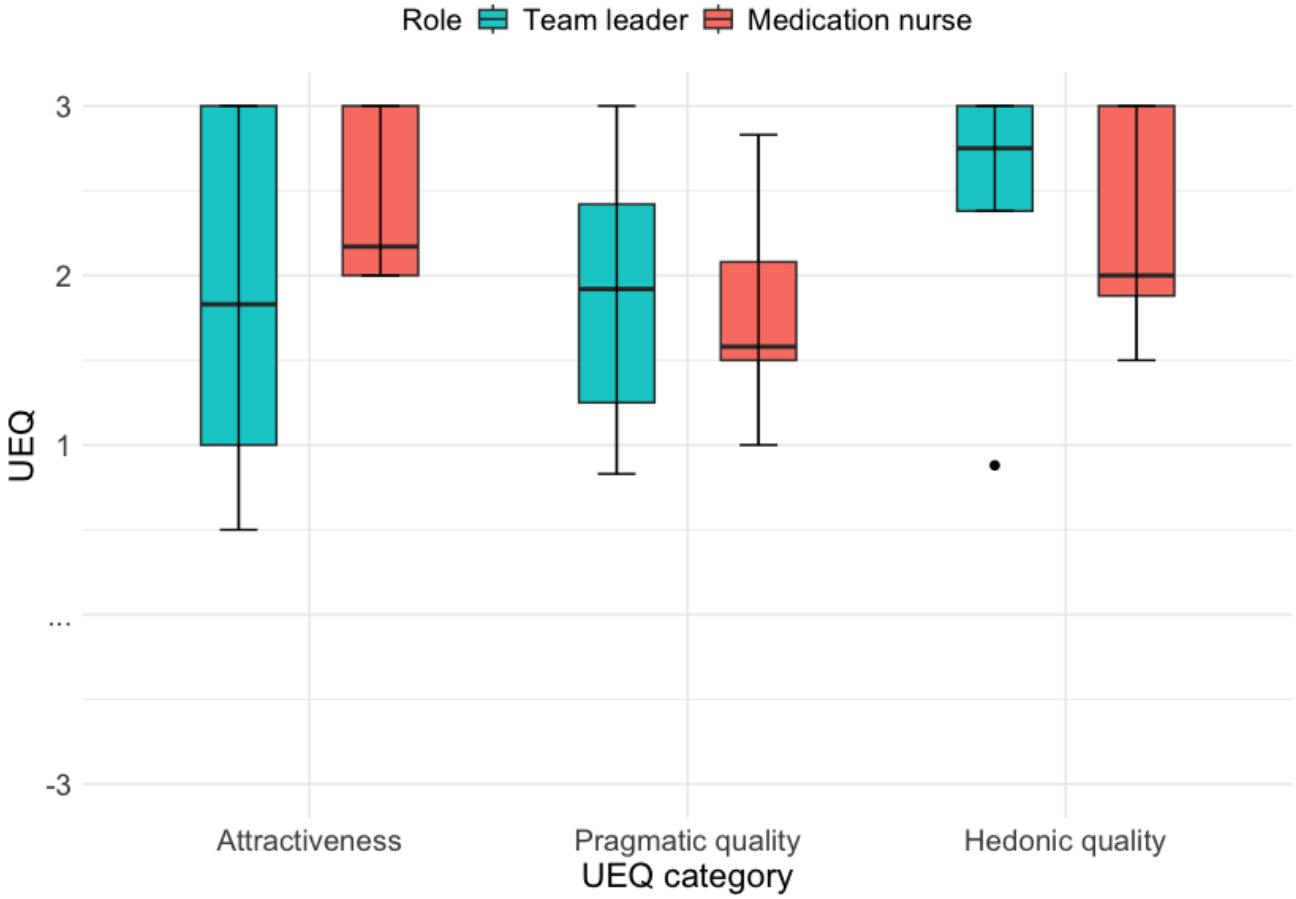
The medication nurse role achieved a higher mean score of 82.00 (SD 11.20, SE 5.02, 95% CI 68.00-96.00), corresponding to an "A" grade (80.80 - 84.00), which falls within the "excellent" usability range (Multimedia Appendix 2). Although the point estimate suggests a stronger perceived usability for medication nurses, the overlapping CIs between roles indicate that differences should not be interpreted as definitive in this pilot study. Overall, both roles reported favorable usability perceptions, with variability reflecting limited precision.

Perceived User Experience

High-Level Results: Attractiveness, Pragmatic Quality, and Hedonic Quality

Perceived user experience was assessed using the UEQ, capturing participants' subjective evaluations across attractiveness, pragmatic quality, and hedonic quality. The following results summarize mean scores and associated uncertainty for each dimension by clinical role (Figure 5).

Figure 5. Comparison of User Experience Questionnaire (UEQ) scores—attractiveness, pragmatic quality, and hedonic quality—across roles. Both groups rated the system well above benchmark levels.



- Attractiveness: The team leader role scored a mean of 1.87 (SD 1.14, SE 0.51, 95% CI 0.45-3.28), whereas the medication nurse role scored higher, with a mean of 2.43 (SD 0.52, SE 0.23, 95% CI 1.79-3.08). Both scores surpass the above-average benchmark, indicating a favorable overall impression of the system's appeal, but the wider CI for team leaders indicates greater variability in perceived appeal (Multimedia Appendix 3).
- Pragmatic quality: Pragmatic quality scores were similarly positive across roles, with team leaders reporting a mean score of 1.88 (SD 0.87, SE 0.39, 95% CI 0.80-2.97) and medication nurses reporting a mean score of 1.80 (SD 0.69, SE 0.31, 95% CI 0.94-2.66). The overlapping CIs suggest comparable perceived task support.
- Hedonic quality: The team leader role scored a mean of 2.40 (SD 0.89, SE 0.40, 95% CI 1.30-3.50), whereas the medication nurse role scored a mean of 2.28 (SD 0.69, SE 0.31, 95% CI 1.42-3.13). These high scores highlight that users perceived the system as engaging and stimulating, contributing to a positive user experience, but the width of the CIs underscores the preliminary nature of these findings.

Pragmatic Quality Subdimensions

The analysis of pragmatic quality subdimensions (Figure S6 in Multimedia Appendix 1) revealed similar patterns across roles.

- Perspicuity: Both the team leader and medication nurse roles reported a mean score of 1.80. The team leader's result (SD 1.14, SE 0.51, 95% CI 0.39-3.21) and the medication nurse's results (SD 0.76, SE 0.34, 95% CI 0.86-2.74) indicated greater variability in perceived ease of learning among team leaders.
- Efficiency: For task completion speed and support, both roles achieved high mean scores of 2.15. The team leader's score (SD 0.68, SE 0.30, 95% CI 1.31-2.99) and the medication nurse's score (SD 0.38, SE 0.17, 95% CI 1.68-2.62) suggest perceived efficiency benefits, although precision remains limited.
- Dependability: The team leader role achieved a mean score of 1.70 (SD 1.02, SE 0.46, 95% CI 0.43-2.97), whereas the medication nurse role scored slightly lower at 1.45 (SD 1.30, SE 0.58, 95% CI −0.17 to 3.07). These scores indicate that users felt a good level of control (predictable), but the CI spanning zero indicates uncertainty regarding perceived control, highlighting this dimension as an area requiring further investigation.

Hedonic Quality Subdimensions

The analysis of hedonic quality subdimensions (Figure S7 in Multimedia Appendix 1) focused on stimulation and novelty, capturing the emotional and experiential aspects of user interaction with the AR system.

- Stimulation: The team leader role achieved a mean score of 2.25 (SD 0.94, SE 0.42, 95% CI 1.09-3.41), whereas the medication nurse role scored similarly at 2.20 (SD 0.84, SE 0.37, 95% CI 1.16-3.24). These scores suggest that the system is engaging and helps sustain users' interest,

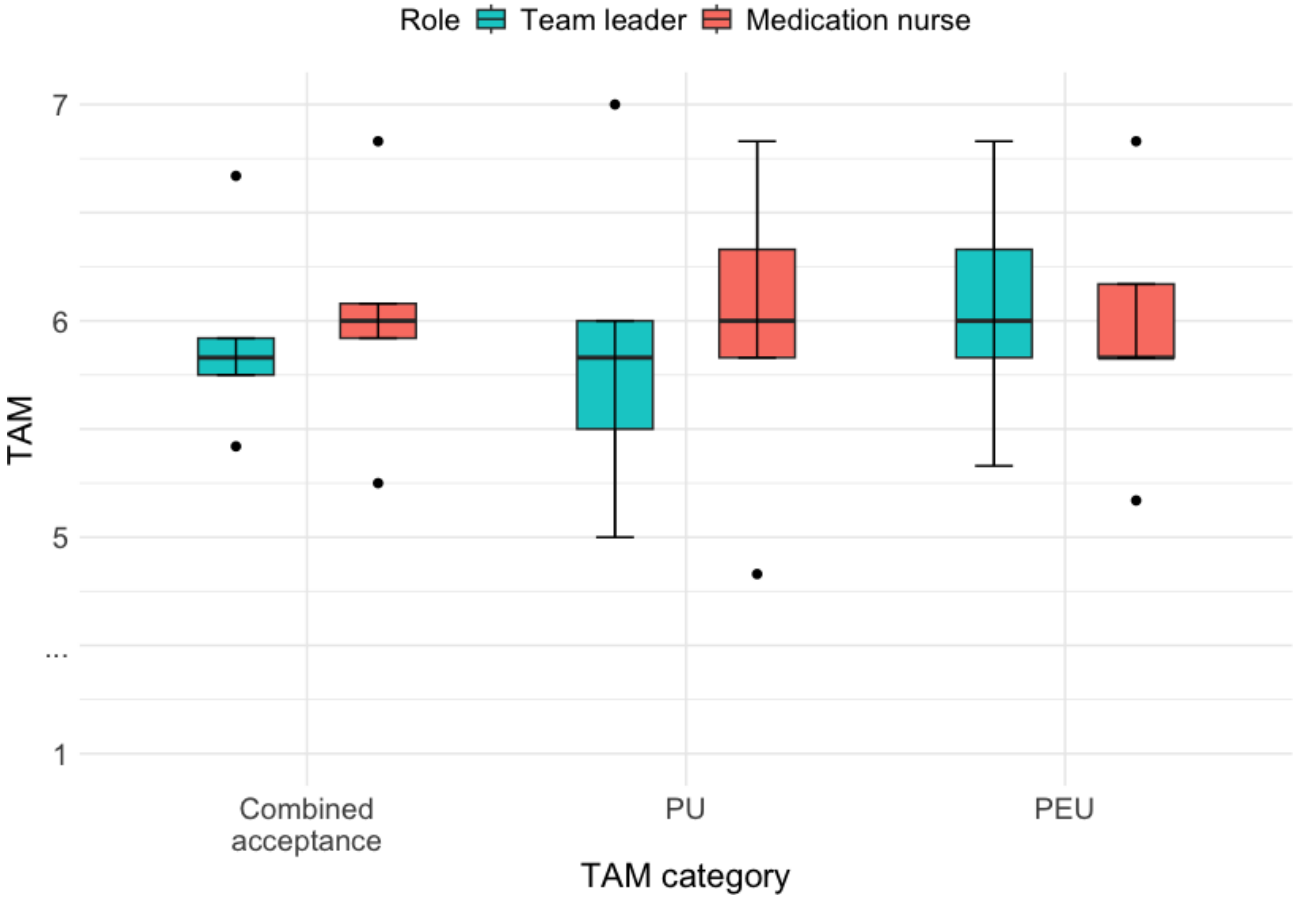
motivating them throughout its use, but overlapping CIs and moderate width reflect limited precision in this pilot evaluation.

- Novelty: This subdimension assesses the system's originality and innovative aspects. The team leader role scored a mean of 2.55 (SD 0.87, SE 0.39, 95% CI 1.47-3.63), whereas the medication nurse role scored a mean of 2.35 (SD 0.86, SE 0.38, 95% CI 1.28-3.42). These results indicate that users perceived the AR system as innovative, contributing to a unique and satisfying experience, but overlapping CIs again reflect limited precision.

Perceived Technology Acceptance

The TAM scores were evaluated across PU and PEU. Combined scores were also calculated to provide an overall measure of acceptance for each role (Figure 6).

Figure 6. Technology acceptance model (TAM) results showing high perceived usefulness (PU) and perceived ease of use (PEU) for both roles, suggesting strong intention to adopt the augmented reality system in clinical training or practice.



- Combined acceptance: The team leader role scored a mean of 5.92 (SD 0.46, SE 0.21, 95% CI 5.35-6.49), whereas the medication nurse role achieved a slightly higher score of 6.02 (SD 0.56, SE 0.25, 95% CI 5.32-6.71). The overlapping CIs suggest broadly comparable acceptance levels.
- PU: The team leader role achieved a mean score of 5.87 (SD 0.74, SE 0.33, 95% CI 4.95-6.78), whereas the medication nurse role scored slightly higher at 5.96 (SD 0.74, SE 0.33, 95% CI 5.05-6.88). While this indicates strong acceptance, CI width reflects uncertainty inherent to the small sample size.
- PEU: The team leader role scored a mean of 6.06 (SD 0.56, SE 0.25, 95% CI 5.37-6.76), whereas the medication nurse role scored similarly at 5.97 (SD 0.60, SE 0.27, 95% CI 5.22-6.72). These point estimates indicate strong acceptance, but CI width again reflects uncertainty.

Discussion

Summary of Main Findings

This study examined the feasibility and perceived usability, user experience, and acceptance of a role-specific AR decision support system designed for resuscitation team leaders and medication nurses. Consistent with the study objectives, clinicians generally perceived the system as usable, intuitive, and acceptable within a high-fidelity simulation context. Perceptions varied by role, reflecting differences in information needs, visual attention demands, and task responsibilities during CA management. These findings suggest that role-tailored AR interfaces are a potential tool for supporting cognitive work in resuscitation settings [15,27], while also underscoring that the present system represents an early-stage, proof-of-concept interface evaluated primarily through subjective measures.

Interpretation of Findings and Relation to Prior Work

Across instruments assessing perceived usability, user experience, and technology acceptance, participants reported favorable impressions of the AR system. These results indicate that clinicians were able to understand and interact with the interface with minimal difficulty and perceived the system as appropriate for use in a simulated resuscitation workflow. Differences in perceived usability and acceptance between team leaders and medication nurses likely reflect role-specific cognitive and visual demands, as team roles in dynamic, safety-critical environments impose distinct situation awareness requirements and attentional burdens depending on task responsibilities and information density [28]. In particular, the team leader interface presented a higher density of information intended to support situational awareness and decision coordination, which may have contributed to comparatively lower—but still positive—perceptions of ease of use.

Participants' responses suggest that the interface aligned with expectations for workflow support in emergent care contexts, where information must be rapidly accessible and interpretable at a glance. These findings are consistent with prior AR and mixed-reality research in clinical and safety-critical domains, which has shown that spatially anchored, role-relevant visual cues can be perceived as supportive when they reduce the need for external references and centralize task-critical information [29,30]. Importantly, these findings reflect perceived support rather than measured improvements in performance, workload, or coordination.

Several participants noted during postsimulation debrief discussions that the AR displays helped them maintain focus on the resuscitation process and reduced reliance on external reference materials. These observations represent subjective reflections elicited during informal debriefing rather than systematically collected performance data and should therefore be interpreted as experiential insights rather than evidence of objective benefit.

Ease of Use, Learnability, and PU

High PEU and learnability indicate that clinicians felt they could quickly become comfortable with the interface, an important consideration for emergency contexts where training time is limited [31]. The visual organization of information, use of glanceable timers, and limited interaction complexity appeared to align with clinicians' expectations for decision support during resuscitation [28,29].

Clinicians also viewed the system content as relevant and supportive of their respective roles, as reflected in ratings related to PU and pragmatic quality. These perceptions are consistent with the underlying design rationale of emphasizing medication-specific information for nurses and algorithmic pathway cues for team leaders. Although prior research suggests that highly usable systems can reduce cognitive load and support more fluid task execution [27], such perceptions should not be interpreted as evidence of improved task performance, guideline adherence, or efficiency. None of these outcomes were directly measured in the current study, and future evaluations must incorporate objective task-level metrics to determine whether perceived utility translates into measurable clinical benefits.

Novelty, Engagement, and Hedonic Experience

Participants rated the AR system highly on hedonic quality dimensions—novelty and stimulation—indicating that the interface was perceived as original, engaging, and distinct from existing tools. These responses reflect perceived innovativeness and experiential engagement rather than satisfaction or effectiveness. Such hedonic responses are encouraging for simulation-based training contexts, where engagement can influence motivation and willingness to adopt new tools [23]. Especially in AR, prior research demonstrated that spatially registered visual cues can increase engagement and perceived control [15,18,19].

At the same time, novelty effects are well documented in evaluations of emerging technologies, particularly during short-term exposure. Perceptions of engagement and stimulation may change with repeated use or prolonged deployment, emphasizing the need for longitudinal studies to assess sustained acceptance and experiential quality over time.

Role-Specific AR Design Implications

A central contribution of this study is the identification of actionable design principles for AR support during CA resuscitation. The iterative prototyping process revealed that AR interfaces should prioritize role-relevant information to minimize unnecessary visual load, use dominant and easily glanceable timers for actionable intervals such as CPR cycles and epinephrine dosing, maintain algorithmic transparency to allow clinicians to view the full pulseless arrest algorithm, and organize spatial layouts clearly by separating medication instructions, procedural steps, and timing cues. These principles provide practical guidance for developers of future AR support tools. While these design choices were intended to support coordination, anticipation, and situational awareness, their operational impact on team performance and guideline adherence remains to be empirically evaluated in future studies. These design considerations align with prior work on situation awareness, cognitive aids, and role-specific information presentation in safety-critical and resuscitation contexts [28-30].

Real-World Implementation Considerations

Although the system achieved promising perception-based results in a controlled simulation environment, translating AR decision support into real clinical workflows presents substantial challenges. Cost, hardware maintenance, device sterilization, and user training remain key considerations for AR deployment in clinical settings [13,30]. Furthermore, seamless interoperability with existing electronic health record systems, secure handling of patient data, and efficient user training are essential for successful integration. Although none of our participants reported discomfort related to the headset bulkiness or fatigue, future iterations should explore lightweight, cost-effective head-mounted devices and web-based synchronization frameworks that ensure data security and workflow continuity. Addressing these implementation barriers will be critical to realizing the clinical impact of AR-based decision support systems. Given that the current evaluation

involved standardized scenarios, conclusions about clinical applicability should be viewed as preliminary.

Limitations and Future Work

While the AR system demonstrated high usability, user experience, and technology acceptance, several limitations should be acknowledged. The most notable limitation is the small sample size (n=10), which restricts statistical generalizability and inferential power. Participants had prior exposure to an early prototype, which may introduce some bias in perceived usability and novelty but also provide more implementation-focused feedback due to their familiarity with the system. Future studies will distinguish between first-time and repeat users to maintain objectivity.

This study was designed primarily to assess initial technical and interaction viability and user experience rather than to test hypotheses or perform comparative statistics. Accordingly, future formal evaluations with larger and more diverse participant samples are planned to validate reproducibility and strengthen external validity. The current evaluation also relied primarily on subjective self-report measures. Incorporating objective performance metrics—such as time to defibrillation, time to epinephrine administration, adherence to CPR cycles, and error frequency—will be crucial in future work. These indicators, combined with physiological or behavioral measures (e.g., eye-tracking, gaze-based workload assessment, or speech-based coordination analysis), can provide richer evidence for the system's real-world effectiveness in improving team performance and reducing cognitive load. Additionally, the study's simulated pediatric CA scenario, while useful for evaluation, may not capture the full range of real-world situations that resuscitation teams might encounter. Expanding the system's evaluation to include a broader range of scenarios could improve its generalizability across diverse clinical environments.

To address these limitations, future research will involve testing the AR system in various CA simulation scenarios to assess its adaptability and reliability before clinical implementation. No major hardware stability issues were observed during testing, and participants, including those wearing corrective glasses, were able to use the device comfortably. Nonetheless, extended use may cause mild visual fatigue or vertigo in a small subset of users, as reported in prior AR literature [27], which warrants monitoring during longer clinical sessions. Plans include conducting an international multisite study with a larger, more diverse participant pool to gain broader insights. This study will also involve incorporating the AR tool into an expanded CPR support system, including additional tools such as a widescreen display for team information visualization, a tablet-based progress monitoring tool providing real-time clinical data, and advanced control interfaces. To gain deeper insights into user performance and behavior, follow-up studies will incorporate objective performance metrics, such as task completion time, gaze tracking, and speech analysis. These metrics will be instrumental in evaluating the system's effectiveness in real-world, high-stakes environments, with the ultimate goal of refining and enhancing its role-specific support functionalities for future clinical use.

Conclusions

This study demonstrates the feasibility and favorable perceived usability, user experience, and acceptance of a role-specific AR decision support system designed for pediatric resuscitation team leaders and medication nurses. Clinicians perceived the system as intuitive, clear, and appropriately tailored to their roles, supporting its potential use in simulation-based training and early-stage clinical exploration. Importantly, the present findings are limited to perception-based outcomes and do not provide evidence of improved performance, workload reduction, or guideline adherence. Rather, this work establishes a foundation for future evaluations that integrate objective measures and assess real-world impact. More broadly, the study illustrates how role-specific AR interfaces can be systematically designed and formatively evaluated as cognitive aids in high-stakes, team-based health care settings.

The innovation of this work lies in its explicit focus on role-specific, in-view AR decision support, which differs from prior studies that primarily evaluated role-agnostic cognitive aids delivered via tablets, posters, or nonadaptive AR displays. By empirically examining clinicians' perceptions across distinct team roles, the study contributes early evidence and practical design guidance for developing role-aware AR interfaces aligned with differing cognitive demands and workflows. In real-world contexts, such role-tailored AR systems may inform the design of next-generation simulation training tools and guide the integration of wearable decision support into clinical resuscitation environments, contingent on future validation using objective performance metrics.

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All content in this manuscript was conceived and written by the authors. OpenAI ChatGPT-5.2 (2025) was used solely as an editorial aid to improve language quality, such as identifying grammatical issues and suggesting alternative phrasing to enhance clarity and readability of the authors' original text. No artificial intelligence–generated content was incorporated verbatim. All suggestions were critically reviewed, revised as necessary, and approved by the authors, who retain full responsibility for the content and accuracy of the manuscript. Use of generative artificial intelligence was limited to language refinement.

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Data Availability

The datasets generated and analyzed during this study are not publicly available but are available from the corresponding author upon reasonable request.

Authors' Contributions

The study's initial ideation was led by AC, JNS, and SM, with contributions to the overall study design from RK, YL, JD, DCD, ADM, AR, SKO, FE, and KK. RK was responsible for system development, while RK, AC, JD, YL, DCD, and KK conducted data collection. Data analysis was carried out by RK, HN, and KK. Manuscript writing was undertaken by RK, AC, HN, and KK, with YL, JD, DCD, JNS, SM, ADM, AR, SKO, and FE providing critical review and editing. All authors have reviewed and approved the final version of the manuscript and take responsibility for the integrity and accuracy of the research. The corresponding author affirms that the manuscript is an honest, accurate, and transparent account of the study and confirms that any deviations from the original study plan have been documented.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Supplementary figures illustrating augmented reality (AR) interface design prototypes, system architecture and control interfaces, and usability evaluation results for the role-specific AR decision support system.
[DOCX File, 7546 KB - xr_v3i1e72013_app1.docx]

Multimedia Appendix 2
Grading scale for System Usability Scale scores with corresponding percentile ranges, usability adjectives, and acceptability levels [32].
[XLSX File, 17 KB - xr_v3i1e72013_app2.xlsx]

Multimedia Appendix 3
Interpretation criteria for User Experience Questionnaire scores across different scales [33].
[XLSX File, 17 KB - xr_v3i1e72013_app3.xlsx]

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Abbreviations

ACH: Alberta Children's Hospital
AR: augmented reality
CA: cardiac arrest
CPR: cardiopulmonary resuscitation
PEA: pulseless electrical activity
PEU: perceived ease of use
PU: perceived usefulness
SUS: System Usability Scale
TAM: technology acceptance model
UEQ: User Experience Questionnaire
UI: user interface

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Immersive Virtual Reality–Supported Cognitive-Behavioral Therapy for Patients With Mild to Borderline Intellectual Disabilities and Substance Use Disorders: Two Exploratory Studies

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Abstract

Background: Substance use disorders (SUDs) are prevalent and characterized by high relapse rates. Individuals with mild to borderline intellectual disability (MBID) are more likely to develop SUDs and face barriers within treatment related to difficulties they experience with abstract thinking, verbal skills, and generalizing learned strategies to real-world contexts. Therefore, experiential, context-rich approaches are needed that reduce reliance on retrospective verbal reflection, support in-context identification of triggers, and allow the rehearsal of coping responses. Immersive virtual reality (IVR) may provide realistic, safe environments where patients with SUD and MBID can practice cognitive and behavioral skills with visual and practice-oriented materials.

Objective: This study aimed to generate design input for the development and clinical integration of IVR-supported therapy for individuals with MBID and SUD. Specifically, Study 1 explored alcohol-related triggers in patients with alcohol use disorder, whereas Study 2 examined the feasibility and acceptability of practicing nicotine-related coping strategies in patients with nicotine dependence (ND).

Methods: Two explorative studies were conducted at an inpatient clinic for patients with MBID and SUD in the Netherlands. Study 1 included 10 adults with alcohol use disorder and MBID who participated in interviews to determine relevant risk situations, triggers, and therapeutic goals for IVR-cognitive behavioral therapy (CBT). Study 2 included 10 adults with MBID and nicotine dependence who practiced coping strategies within an existing IVR featuring craving-inducing and craving-reduction scenarios. A multiple-method approach was used to gather input for IVR-CBT development and to explore feasibility and acceptability (user evaluation interviews, the Questionnaire of Smoking Urges, and Visual Analog Scale ratings).

Results: In study 1, we identified high-risk situations, including at-home routines (eg, sitting on the couch watching football), supermarkets (eg, confrontation with alcohol and advertisements), social gatherings (eg, invitations and peer pressure), and being outside or traveling (eg, public transport or passing alcohol-related places). Triggers clustered into multisensory cues (eg, seeing or smelling alcohol), social influences (peer pressure and interpersonal conflict), affective states (tension, distress, boredom, or euphoria), and personal habits (eg, rewarding oneself or associations with money). Participants expressed interest in using IVR to identify triggers, discuss affective states, and train refusal skills. In study 2, IVR elicited nicotine craving, which increased during cue exposure and decreased during tutorial and coping phases. The coping elements embedded in IVR included relaxation (eg, mindfulness or breathing exercises), distraction (eg, virtual pets and interactive games), and physical activity (eg, walking or sports).

Conclusions: IVR-CBT elements appear feasible and acceptable in inpatient MBID care with appropriate support. Findings provide patient-derived design insights for integrating trigger identification and coping rehearsal within IVR. Future work should use an iterative, user-centered design approach based on validated CBT-related techniques (eg, functional analysis or coping, or skills training) and compare IVR-CBT with CBT as usual to understand benefits and risks for patients and therapists.

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KEYWORDS

immersive virtual reality; cognitive behavioral therapy; substance use disorder; alcohol use disorder; nicotine dependence; mild intellectual disability; borderline intellectual functioning; craving; relapse prevention; user-centered design

Introduction

Background

Substance use disorders (SUDs) are highly prevalent and complex psychiatric conditions with a high disease burden [1]. Individuals with mild to borderline intellectual disabilities (MBID) are at an increased risk for developing SUDs [2,3]. MBID covers both persons with mild intellectual disability (MID) and borderline intellectual functioning (BIF) [4], and in the Dutch clinical context, it is defined by an IQ between 50 and 85, accompanied by limitations in adaptive functioning with onset during the developmental period. Individuals with MBID often experience cognitive limitations that affect comprehension, memory, and problem-solving abilities, as well as difficulties in understanding the consequences of substance use, which can increase their susceptibility to SUDs and reduce the efficacy of treatment as usual [2]. Additionally, the prevalence of SUDs among persons with MBID is exacerbated by social vulnerabilities, such as problems with social skills [5], as well as social isolation, trauma, and substance use as a form of self-medication against negative life events [6].

Despite the availability of various psychotherapeutic and pharmacological treatments, maintaining long-term recovery in individuals with MBID can be challenging. As reported by the National Institute on Drug Abuse (2020), relapse rates in the general population who were treated for SUDs vary between 40 and 60 percent. Although specific relapse data for individuals with MBID are limited, relapse rates in this group might be even higher, given the challenges in assessment and standard treatment they may encounter [7,8]. For instance, most individuals with MBID experience communication barriers as they struggle to verbalize their thoughts, emotions, behaviors, and everyday risk situations. Moreover, barriers in skill application are present, as they often experience difficulties with applying newly learned skills from treatment in real-world risky situations [8]. These barriers in communication and skill application can make it more difficult to engage in therapeutic processes such as cognitive behavioral therapy (CBT) that rely on reflective, language-based approaches, which require cognitive and adaptive skills. Although tailored CBT protocols for the dual diagnosis of MBID and SUDs are available in the Netherlands [8,9], they still require patients to remember and reflect on their own behavior within treatment when discussing high-risk situations. Furthermore, generalizing and applying the newly learned coping skills in the real world remains difficult [8]. Consequently, there is a need for experiential, context-rich treatment approaches that reduce the reliance on abstract verbal processing and support in-context rehearsal of coping responses.

From Virtual Reality Exposure Therapy to Immersive Virtual Reality–Based Cognitive Behavioral Therapy

Immersive virtual reality (IVR) offers a promising approach to address the cognitive barriers that people with MBID experience within standard treatments that are based on the principles of CBT. IVR can be described as a computer-generated simulation of a 3D setting by using special electronic equipment [10]. Typically, head-mounted displays (HMDs) are used to immerse the user into a virtual environment (VE). Previous research suggests that IVR might lower learning obstacles by making experiences and training abstract concepts and interrelationships more explicit, understandable, and trainable, thereby improving comprehension for people who struggle with abstract thinking, such as those with MBID [11-13]. This approach eliminates the requirement for disembedded thinking, which refers to the capacity to grasp concepts outside of immediate and physical contexts. This is a skill that individuals with MBID find challenging [14]. Moreover, IVR can facilitate active learning rather than passively receiving information, thus reducing the reliance on abstract reasoning and verbal instructions while fostering skill acquisition [14]. This implies that learning becomes an engaging experience that does not solely rely on a language-based experience. Instead, IVR facilitates skill development through experiential learning, allowing individuals to learn by doing in a safe, controlled setting and acquire new skills without solely relying on language-based instructions [15,16].

Various studies have shown that VEs can elicit realistic (physical) reactions and behaviors in patients with SUD [10,17,18], including tension and substance cravings [13]. Virtual reality exposure therapies (VRET) have been developed based on these “natural” reactions to stimuli in IVR, for example, within the domain of anxiety disorders [19]. Following this initial success, research has also explored possible uses of VRET for SUDs, drawn by its ecological validity in realistically eliciting cue reactivity, such as drug craving and psychophysiological reactions (eg, increased heart rate and sweating) to stimuli associated with substance use [20].

However, the effectiveness of VRET for SUDs remains questionable. While pilot studies using VRET for SUDs led to cue reactivity and participant satisfaction, as well as expectations of clinical benefit, a 2021 review indicates that this has not yet been demonstrated in research on clinical effectiveness [21]. This is supported by an earlier review from Segawa et al [22], who stated that although IVR is effective at eliciting craving, VRET treatment outcomes vary. One hypothesis is that exposure in the context of addiction does not lead to extinction but rather reactivates a pathologically disturbed reward system, unlike anxiety disorders. As a result, VRET might even increase the risk of relapse [23], which is consistent with the lack of effectiveness of regular exposure therapies for SUDs [24]. Taken together, the evidence at the time of this writing indicates that VRET is insufficient for lasting change and that it may be essential to integrate, for example, CBT techniques in IVR interventions to actively understand triggers and train coping behaviors. This approach aligns with a literature review by Taubin et al [25], who found that IVR protocols integrating mindfulness practice, cognitive reappraisal, or other

emotion-regulation tasks alongside IVR were more likely to achieve clinically meaningful effects on substance-use outcomes. Experimental data support this conclusion; in a randomized study, smokers who actively crushed virtual cigarettes, an IVR task that requires users to enact an immediate coping response, achieved significantly higher abstinence rates than smokers who performed a neutral control task [26]. These findings indicate that active rehearsal of coping strategies rather than exposure alone is essential for therapeutic benefits. Accordingly, an IVR protocol used in an active learning format that engages patients in practicing coping responses to trigger-related craving may positively influence internal biases and promote behavior change.

Building on these insights, embedding active learning tasks into an IVR can lead to interactive, user-centered interventions that are more compatible with the needs of individuals with MBID and SUDs. IVR-CBT for SUDs allows patients to safely confront triggers by exploring maladaptive thought patterns and gradually exposing them to drug-craving-provoking situations while practicing coping strategies in a secure, controlled VE. Moreover, IVR-CBT provides a supportive learning environment that allows users to experiment with alternative behaviors in a step-by-step manner, thereby enabling cognitive restructuring and learning of suitable behavioral responses to SUD-related symptoms. This aligns with the core objectives for SUDs in standard addiction care treatments that are based on CBT principles [27], including psychoeducation, skill development for coping strategies, developing more adaptive thinking patterns, strengthening problem-solving skills in a practical manner, and relapse prevention through self-control and reinforcement of positive behaviors [28]. However, research in interdisciplinary teams is needed to understand design requirements to develop IVR-CBT interventions, as well as implementation into treatment as usual.

This study reports on 2 explorative studies conducted with patients in a specialized addiction clinic for individuals with MBID and SUD. Study 1 aimed to identify patient-reported high-risk situations and craving triggers relevant to alcohol use during preparation for temporary clinical leave. Study 2 aimed to explore the feasibility and acceptability of engaging patients with MBID in an IVR protocol that induces nicotine craving while embedding coping components in virtual reality (VR; eg, distraction, relaxation, and physical activity). Feasibility was defined as completion of IVR phases and tolerability (eg, need for support/breaks, discontinuation), and acceptability was defined as perceived realism and perceived usefulness. Given the substance-specific focus of each study, findings are interpreted as exploratory and design-oriented, without assuming transferability of identified triggers or coping preferences across substances. Across both studies, our overarching goal was to generate initial design requirements and clinical integration considerations for future IVR-CBT modules for MBID and SUD populations.

Methods

Study 1: Identifying High-Risk Situations and Triggers for IVR-CBT

Study Design and Participants

We explored high-risk situations and triggers to prepare patients with MBID and alcohol use disorder (AUD) for temporary clinical leave during treatment as usual. In total, 10 adults with MBID, receiving inpatient AUD therapy, were included using convenience sampling. Participants were recruited by their treating therapist within the inpatient clinic when they met the study criteria and were considered able to participate. Diagnostics for MBID were conducted by psychologists in the addiction clinic or by other medical institutions in the care chain of patients (eg, disability care). Exclusion criteria included severe psychiatric disorders (eg, psychosis) or active substance use. Eight of ten patients had previous experience with IVR, mainly via participation in the previous studies by our research group. Data were collected from January to April in 2021 in a Dutch addiction clinic specialized in the treatment of patients with MBID and SUD.

Ethical Considerations

This research was approved by the Saxion University of Applied Sciences in Enschede, as well as the scientific board of Tactus Addiction Care (OZP 26-112020). Personal identifiable information was archived separately from research data at Tactus Addiction Care to protect our patients from data breaches. Moreover, we pseudonymized data and deleted related audio recordings after transcription. Before starting the interviews, participants signed an informed consent. Patients received no compensation for participation.

Materials and Procedures

We conducted semistructured interviews with 7 open questions to explore (1) how patients would prefer to use IVR for practicing the clinical leave (2 questions), (2) which alcohol-related situations (1 question) induce alcohol craving, and (3) which triggers (1 question) induce alcohol craving. The interview guide (Multimedia Appendix 1) was pilot tested with 2 patients prior to data collection. The researcher explained the study procedure by using examples (eg, photos and videos) from the “Go up in smoke” project [13] to familiarize patients unfamiliar with IVR with relevant concepts. The “Go up in smoke” project focuses on the induction of nicotine craving using triggers and the reduction of craving using coping skills in IVR. Subsequently, semistructured interviews were held in a quiet office in the addiction clinic and were audio recorded.

Data Analysis

The audio files were transcribed verbatim and analyzed based on Braun and Clarke’s reflexive thematic analysis approach [29,30]. For this, the researcher (Berlind van Ast) followed the 6-step protocol: for (1) data familiarization, the researchers listened to the recordings and read the transcripts. Subsequently, (2) relevant segments in the data were identified, coded, and collated. Then, (3) initial themes were generated using the coded data and (4) reviewed by revisiting themes with respect to the

aims. Finally, (5) themes were defined, and the (6) report was produced. For this, we used the qualitative data analysis program Atlas.ti (v.9; ATLAS.ti Scientific Software Development GmbH).

During this process, researchers (Berlind van Ast and Jolien Jongeling) reflected together on themes generated during the 6-step analysis (steps 4 and 5), as well as during meetings with supervisors. Both researchers hold a degree in advanced nursing studies and were working in the addiction clinics at the time of data collection. Therefore, both researchers possess previous knowledge about the target group, as well as skills to engage in research with the MBID population. However, previous experiences with addiction care and the context of this research focusing on the IVR-CBT paradigm may influence the confirmability and transferability of findings.

Study 2: (Don't) Go Up in Smoke, Exploring Coping Strategies to Reduce Nicotine Craving in IVR

Study Design and Participants

In study 2, we implemented and evaluated coping skills in IVR that were derived from self-control techniques (eg, distance, distraction, and declare) that are taught during the less booze or drugs [9] treatment for patients with comorbid MBID. For this, we explored typical risk-coping scenarios in IVR to reduce nicotine craving in a convenience sample of 10 non–nicotine-deprived adults with MBID and nicotine dependence (ND) (Fagerström ≥5) undergoing inpatient treatment in a Dutch addiction clinic. Participants were recruited by their treating therapist when they met the study criteria and were considered able to participate. Diagnostics for MBID were conducted by psychologists in the addiction clinic or by other medical institutions in the care chain of patients (eg, disability care). Exclusion criteria included a history of migraine, epilepsy, motion sickness, severe psychiatric disorder (eg, psychosis), and use of nicotine replacement therapy to protect participants from IVR-induced symptoms (eg, cybersickness and hallucination) induced by the IVR device or, in the case of nicotine replacement therapies, to avoid introducing bias on the data collected. Only one of the 10 patients had prior experience with IVR. Data were collected from January to April 2021 in a Dutch addiction clinic specialized in the treatment of patients with MBID and SUD.

Ethical Considerations

Ethical approval as nonmedical research was given by the medical ethics board of the MST hospital in Enschede (K19-34). Moreover, this work was approved by the scientific board of Tactus Addiction Care. Personal identifiable information was archived separately from research data at Tactus Addiction Care to protect our vulnerable patients from data breaches. Moreover, we pseudonymized data and deleted related audio recordings after transcription.

All participants were welcomed by the researcher and thoroughly informed about the research procedure. After informed consent was obtained, the audio and screen recordings were started. The participants received no compensation for participation.

Measures

ND was assessed with the Dutch version of the Fagerström Test for nicotine dependence (FTND) [31]. The FTND is a 6-item questionnaire assessing ND severity with scores ranging from 0 to 10. Scores of 0 - 2 indicate a light dependence, 3 - 5 a moderate dependence, 6 - 7 a severe dependence, and 8 - 10 a very severe dependence.

Nicotine craving was assessed with the Questionnaire of Smoking Urges Brief (QSU-Brief) and by using a Visual Analog Scale (VAS). The QSU-Brief is a 10-item questionnaire assessing the urge to smoke [32]. Scores on each item range from 1 ("Strongly disagree") to 7 ("Strongly agree"). The total score is obtained by calculating the mean of the 10 items. The VAS is a single-item scale ranging from 0 to 10, where 0 is interpreted as "no craving" and 10 as "severe craving."

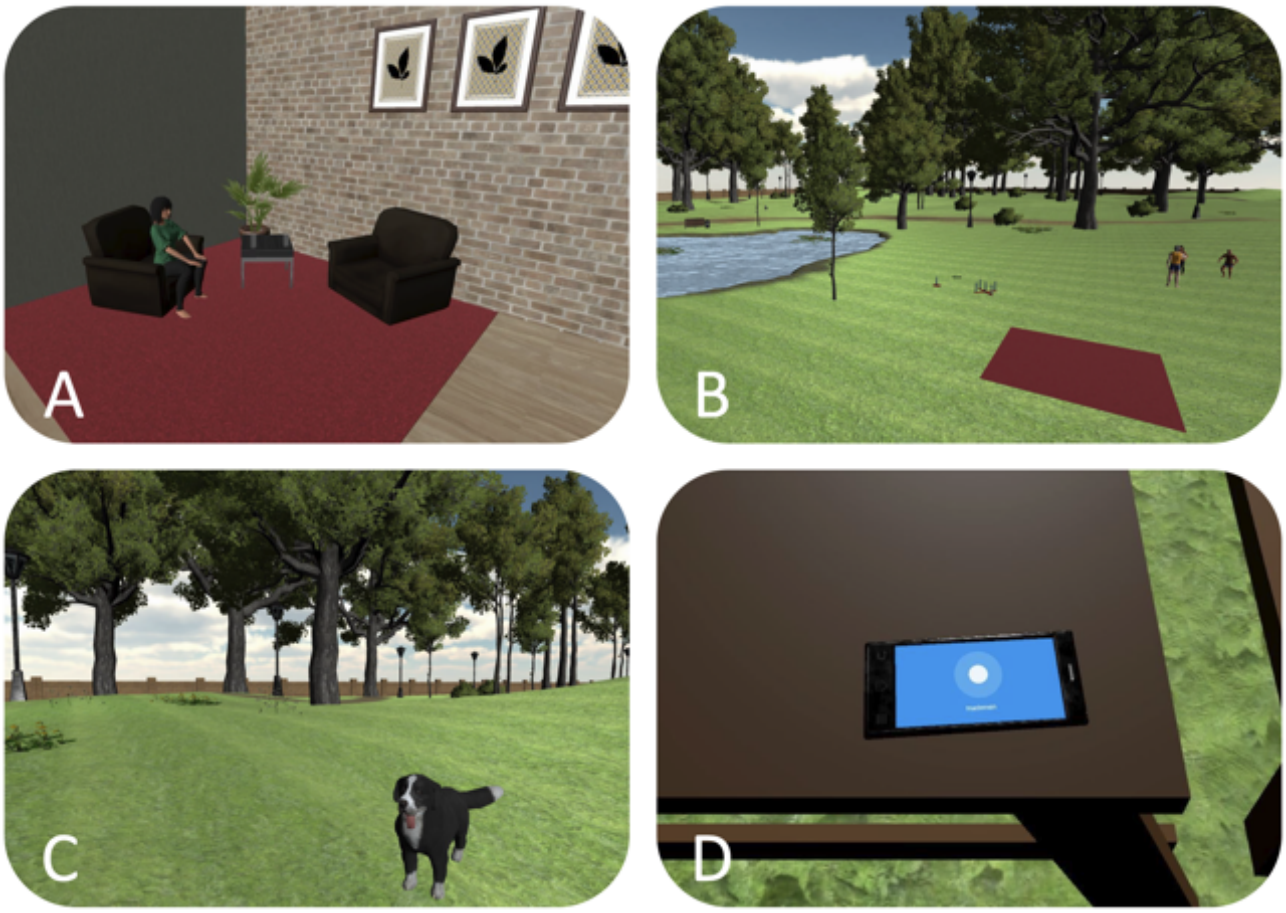
A semistructured interview (Multimedia Appendix 2) with 14 open questions was conducted to explore (1) VE to induce and reduce nicotine craving (3 questions), (2) explored coping strategies to reduce nicotine craving (5 questions) and alternatives in IVR to reduce nicotine craving (5 questions), and (3) potential applications of IVR during treatment (1 question).

Hardware and VE

We used an HTC VIVE Pro Eye HMD (HTC Corp), 1440×1600 pixels per eye (2880×1600 combined), a 90 Hz refresh rate, and an 110-degree field of view, base stations, controllers, and a compatible laptop to display the IVR to the patient.

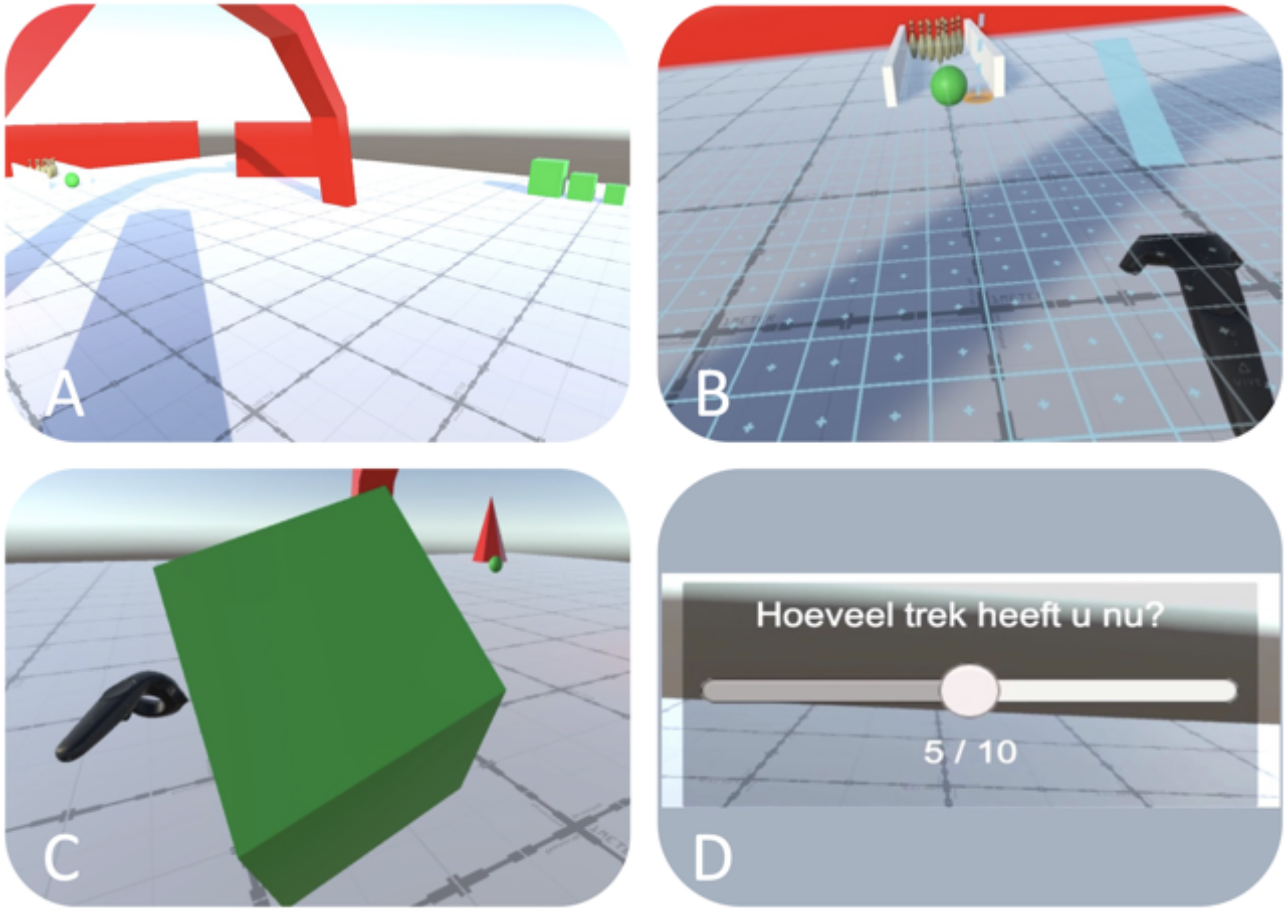
The VE was developed in Unity3D (v.2019.2.3f1; Unity Technologies) using the SteamVR Software Development Kit (Valve Corporation) and was partially adapted from previous work by our department [13], containing two main scenarios: (1) craving induction and (2) reduction (see Figures 1A-1D). The craving induction scenario comprised 3 main areas [13], including a crossroad with a bus stop, at home with a garden, and a restaurant with a terrace and smoking goods vendor. In contrast, the craving reduction scenario comprised 2 environments, including a therapy room with 2 virtual humans guiding 2 different mindfulness exercises that were prerecorded with a psychomotor therapist, as well as a virtual cat in the front yard, a park with a lake, a walkway, sporting agents, a blanket with calming music, a ring toss game, a badminton set, a dog that can be taken for a walk, and benches with a virtual smartphone to conduct a visual breathing exercise. Audio cues respecting the restaurant, interactive humans, cigarettes, blowing wind, running water, and calming music were used to deepen immersion. Participants were able to use teleport locomotion and an approximately 2×2 m room-scale area for natural locomotion.

Figure 1. The virtual environment (VE) for craving reduction. (A) Mindfulness via a virtual therapist, (B) Park with sporting virtual humans, relaxation areas, and games, (C) Walk in the park with a dog, and (D) Breathing exercises on a virtual smartphone.



To train patients in using the controllers and ensure habitation within the IVR, a neutral tutorial was used with specific interactions (ie, grabbing objects or teleporting) by using a plane with a walking track, 3 interactable cubes, and a bowling alley (see Figure 2A-2D).

Figure 2. The tutorial environment to train interactions in immersive virtual reality (IVR), including a (A) "Walking track" to train teleporting, (B) "Bowling alley" to grab and throw a bowling ball, (C) three interactable cubes of different sizes to be stacked, and (D) Visual Analog Scale (VAS) for craving assessments.



Procedure

The research was carried out in a quiet room in an addiction clinic to enhance an ecologically valid surrounding that replicated the usual treatment setting. The procedure (maximum 90 min) was divided into five phases: (1) preparation (≈15 min), (2) tutorial (≈10 min), (3) trigger-induced craving (≈15 min), (4) coping skills and craving reduction exploration (≈15 min), as well as (5) postquestionnaires (≈30 min). During the preparation, demographics and baseline characteristics (ie, FTND and QSU-Brief) were assessed. If necessary, patients were allowed small breaks during phases 1 - 5 without leaving the room (eg, to smoke). At the beginning of the sessions, participants engaged in a short tutorial session in a neutral VE to become familiar with the HMD and controls and rate their craving using the VAS. Upon completion, participants removed the HMD and were verbally asked the QSU-Brief again before entering the cue reactivity environment. Participants were asked to wear the HMD again and conduct a guided exploration (see [13] of 5 specific situations aiming to induce cravings, including bus stop, restaurant terrace, a vendor with smoking goods, an at-home environment with a garden, and a man sitting on a bench smoking). After completing the craving induction stage, patients were instructed to interact with various coping skills, including distraction (ie, breathing and mindfulness exercises, sport, relaxation, and animals), distance (ie, walk in park or go outside), different thinking, different acting (ie, say "no" when a cigarette is offered, drink a soft drink, or use a nicotine patch), declaring (ie, use a virtual phone to call for help), which were derived from existing therapy protocols for people with dual diagnosis [9]. During both phases, patients were asked to rate their cravings after each interaction using the in-game VAS, followed by removing the HMD and completing the QSU-Brief. Finally, the semistructured interview was conducted verbally with participants. During the use of the HMD, patients' therapists were close by to provide help if needed.

Data Analysis

The audio files were transcribed verbatim and analyzed based on Braun and Clarke's reflexive thematic analysis approach [29,30]. For (1) data familiarization, the researcher (Jolien Jongeling) listened to the recording and read the transcript. Then, (2) relevant segments were identified, coded, and collated. The (3) initial themes were generated using the coded data and (4) reviewed by revisiting themes with respect to the dataset and goal. Finally, (5) the themes were defined, and the (6) report was produced. For this, we used the qualitative data analysis program Atlas.ti (v. 9). Data from the QSU-Brief and VAS were analyzed descriptively using RStudio (v. 1.3.1093; PBC).

During this process, researchers (ie, Jolien Jongeling and Berlind van Ast) reflected together on themes generated during the 6-step analysis (steps 4 and 5), as well as during meetings with supervisors (ie, SL and JV). Both researchers pursued a master's degree in advanced nursing studies and worked in the addiction

clinic described in both studies. Therefore, both researchers possess previous knowledge about our target group, as well as skills to engage in research with the MBID population. However, previous professional experiences and the context of this research with a focus on the IVR-CBT paradigm may influence the confirmability and transferability of findings to other settings.

Results

Study 1. Identifying High-Risk Situations and Triggers for IVR-CBT

Sample Description

Participants (n=10) had a mean age of 40.5 (9.7) years, and most identified as female (n=6). The sample included patients with BIF (n=7) and MID (n=3). Notably, most participants (n=7) had prior IVR experience from the "Go up in smoke" project.

High-Risk Situations and Triggers That Elicit Alcohol Craving

The participants identified high-risk situations (see Table 1), including at home, supermarkets, social gatherings, and being outside.

In the home environment, participants mostly described the living room to elicit alcohol habits, though these situations are usually individual, as others describe the bathroom or kitchen. Also, the conditions vary from clean to messy (eg, with bottles all around). Regarding the supermarket, participants described associations and confrontation with alcohol cues (eg, advertisement), potentially triggering affective states ("Then my craving goes up and I start sweating and then I just get difficult thoughts. That I have to drink. That everything gets better when you drink. Yes, very nervous, stressful." [P02]). Social gatherings include meetings with families and peers that entail invitations to drink, including peer pressure and conflict situations ("It is when I am with my father, that he triggers me with his negative energy, my living room, and the supermarket." [P1]). Finally, being outside passing beer gardens, supermarkets, or being in public transport (ie, bus and train) is probably causing distress or invitations from others when walking by.

Table . High-risk situations and triggers in patients with mild to borderline intellectual disability (MBID) and alcohol use disorder (AUD).

Theme	Example
High-risk situations	
At home	"As soon as I enter, I sit on the couch, grab a glass and turn on the football. Then I just sit and consume it on my own." (P08)
Supermarket	"You enter the store and then you see, and you are confronted and then you feel that urge for alcohol. And even if I were to walk by, I would still see them, and they would look at me too. They look like: 'don't forget me.' " (P08)
Social gatherings	"Often you will meet someone you know, and they often know that you like a glass of wine and a beer. And then it's: 'hey, come and sit down, nice and cosy.'" (P07)
Being outside	"Put [Dutch city] in there. There they have to do it themselves. Either by bus or by train. You could combine that with those virtual reality glasses, with the person who either has to go by bus or by train and see how the person reacts." (P01)
Triggers	
Multisensory experiences	"I also deliberately don't go through that hallway anymore, but you see the offer when you come in these days and it's actually terrible, like they do it on the TV." (P05)
Social influences	"For example, if someone would like to belong to a group, then that group encourages: 'Hey, join us!' You should put something like that in it. I would experience that as a trigger." (P07)
Affective states	"When I'm high in tension, I tend to go to the store very quickly. Then I'll go get some alcohol to push that away again. To feel relaxed again." (P01)
Personal habits	"I associate money with alcohol because then these are my groceries." (P08)

Triggers (see Table 1) to use alcohol in the abovementioned high-risk settings can be classified into multisensory experiences, social influences, affective states, and personal habits. The participants described seeing, smelling, and hearing alcohol-related cues in daily situations, such as people drinking, (alcohol) advertisements, bottles, supermarkets, soccer on TV (with sound), and (Dutch) music during social gatherings. Social influences comprise the described invitations, pressure, and conflict situations with (relevant) others to elicit strong distress/cravings. Generally, participants described a spectrum

of affective states, such as distress, boredom, and euphoria as causes of alcohol craving. Finally, personal habits, such as rewarding oneself, nice weather, watching TV, having money in one's wallet, or completing work, were also described, often intertwined with the aforementioned triggers (ie, multisensory cues, social influences, and affective states).

Applications of IVR for CBT in Clinical Care

The preferred use of IVR during clinical care in patients with MBID and AUD can be divided into assessment and treatment (see Table 2).

Table . Preferred use of immersive virtual reality (IVR) for cognitive behavioral therapy (CBT) in patients with mild to borderline intellectual disability (MBID) and alcohol use disorder (AUD).

Theme	Example
Assessment	
Identify high-risk situations and triggers	"I will feel safe. Yes, because suppose you really get those craving moments or a panic attack, then you have a backup to rely on." (P01)
Coping skills training	
Discuss feelings during high-risk situations with therapists	"Because you are still in a safe environment, you can better discuss what you are feeling at that moment and how you can best deal with it." (P07)
Training of distraction techniques for coping with alcohol craving	"Practicing with such glasses to look for distraction, that is very important. (.) For example, that I get a trigger to take a walk. So, I didn't do that before, I just remained seated and then went for a walk to the fridge." (P06)
Learn to say "no" when offered alcohol	"Seeing other people drinking seems like a very good thing to practice [with IVR], you will soon encounter that at birthdays, and I just want to be able to do it without it. And if they offer me one then I want to be stronger to say 'no.'" (P05)

For assessment, participants reported the need to identify personal risk situations and triggers using IVR. This includes measuring craving in the given context (by using a VAS) to gain insights into one's own vulnerabilities. Regarding treatment, participants reported the wish to discuss feelings during risk situations with therapists, to train distraction techniques for coping with cue reactivity, and learn to say "no" when offered alcohol, for example, by choosing alternatives. In doing so, participants said they would like to train and rehearse repeatedly before leaving the clinic ("If you have always said 'yes' [to substance use] it is very strange for you to say 'no.' And I think the more you practice that, the easier it gets." [P07]). Most participants indicated a positive intention to use IVR for practicing clinical leave ("Yes, that would be nice, because then you are not immediately placed in the real situation, and you can learn to deal with your feelings and with your craving." [P02]), though some found it redundant or anxiety-evoking ("It was too scary for me. Everything overwhelms you, so to speak." [P10]).

Study 2: (Don't) Go Up in Smoke–Exploring Coping Strategies to Reduce Nicotine Craving in IVR

Sample Description

Participants (n=10) had a mean age of 39 (9.0) years, of which half (n=5) identified as female. The sample included patients with BIF (n=7) and MID (n=3). The FTND was moderate (n=2), severe (n=4), and very severe (n=4), respectively. Patients smoked on average 18.7 (4.2) per day, and most (n=9) had no prior IVR experience.

IVR Craving Induction and Procedural Remarks

All participants reported the IVR to be craving-inducing. Especially, the man offering a cigarette and the bus stop were mentioned to cause severe cravings ("Yes and that man on that bench, who then offers you a cigarette and at that moment you just notice something goes through you, oh yes delicious." [S08]). Though some participants reported prior to using the IVR worries about their abilities to navigate and interact, the researchers observed mostly positive remarks after immersion in IVR. However, 2 patients described anxiety issues related to using IVR ("I do find it a little scary" [S01]), resulting in a single dropout.

Coping Strategies to Reduce Nicotine Craving in IVR

For the implemented coping skills (see Table 3), participants named distraction through games and animals; relaxation (ie, mindfulness and breathing exercises); and physical activity (ie, sport going and for a walk in the park [with a virtual dog]) as coping strategies to reduce nicotine craving in IVR. Moreover, all participants engaged in mindfulness/breathing exercises delivered by virtual humans or smartphones. The strategies were described as appealing, though some described control and concentration troubles ("Then I have to be very quiet. No people around me, because then it won't work." [S10]). Furthermore, engaging in physical activity was pleasant, for instance, through sports and games (eg, bowling, throwing rings, and stacking cubes), as most participants mentioned the neutral tutorial to reduce craving ("I immediately stopped thinking about smoking" [S06]). For animals, people enjoyed petting and walking a virtual dog and playing with a virtual cat, as some missed their pets during their clinical stay. Noteworthy, being busy with IVR was described as distracting by many participants. Coping strategies to add to IVR include yoga, additional sports (eg, football and basketball), meditation, talking to a therapist or other patients, and creative tasks.

Table . Coping strategies to reduce nicotine craving in immersive virtual reality (IVR).

Theme	Example
Distraction	
Interactive games (eg, bowling, ring toss, and stacking cubes)	"But that's because I focused on the actions I had to do, that I focused very much on that actually, so I might actually suppress the urge […]." (S05)
Virtual pets	"But also with my cat, which walks with me to the store, that sort of thing, yes crazy. Yes, I miss that animal so much and then they say it's just a cat. Yeah, it's easy for you to say. I see him as my child." (S10).
Sitting close to water (on blanket hearing music)	"That you were distracted, I think, especially that last one beside the water and then with that dog." (S02)
Talking to therapist or other patients[a]	"[…] that someone tells you that the craving will go away and so on, that you will think about it, that you maybe can let it go a bit better." (S08)
Creative tasks	"The open air, the bench to sit down quietly and eh meditate a bit or if necessary, bring a coloring book, because I still like to color very much." (S05)
Relaxation	
Mindfulness	"It did diminish a little with the relaxation exercises, when I sat in that chair like that for a while." (S08)
Breathing exercises	"[…] of breathing in and out, that's actually a kind of relaxation exercise." (S05)
Physical activity	
Going for a walk in the park (with a virtual dog)	"It was more feeling good again, that dog came running to me and eh you miss that very much here" (S08)
Sports (eg, squats, yoga, basketball, football)	"[…] because it is anyway necessary for my fitness, but also for distraction and yes sport is just better on all fronts." (S04)

[a]Not implemented in our immersive virtual reality coping strategies exploration for craving reduction.

Subjective Craving During Baseline, Tutorial, Craving Induction, and Craving Reduction

Table 4 describes data obtained from the QSU-Brief and VAS across the different measures at baseline (T0), tutorial (T1), craving induction (T2), and craving reduction (T3). The results show tendencies for craving reduction during the tutorial (T1) and coping skills exploration (T3).

Table . Difference in craving on Questionnaire on Smoking Urges Brief (QSU-Brief) and Visual Analogue Scale (VAS) at T0-T3.

Measures	T0	T1	T2	T3
QSU-Brief[a]				
Mean (SD)	3.41 (1.1)	3.04 (1.4)	4.20 (1.5)	3.66 (1.2)
Median (IQR)	3.50 (3.0-3.8)	3.15 (1.6-4.3)	4.35 (3.5-5.2)	3.55 (3.0-4.3)
VAS[b] in IVR[c]				
Mean (SD)	4.22 (2.2)	2.86 (2.8)	5.34 (1.8)	2.50 (2.1)
Median (IQR)	4.00 (4.0-5.0)	2.00 (1.0-4.0)	5.57 (4.6-6.6)	2.00 (1.5-2.8)

[a]QSU-Brief: Questionnaire on Smoking Urges Brief.

[b]VAS: Visual Analogue Scale.

[c]IVR: immersive virtual reality.

Discussion

Principal Findings

This study reported 2 exploratory, design-oriented studies that were conducted in an inpatient MBID setting, examining high-risk situations, triggers, and coping strategies to inform the development and clinical integration of IVR-supported elements for substance-use treatment.

In the first study, qualitative interviews were used to identify alcohol-related high-risk situations, triggers, and patient-defined treatment goals in preparation for temporary clinical leave. Participants identified a range of high-risk situations for AUD, including being at home, in supermarkets, at social gatherings,

in public spaces, or while traveling. Alcohol craving in these contexts was associated with multiple types of triggers, including multisensory cues, social influences, affective states, and personal habits. Participants described these alcohol-related high-risk situations as challenging and expressed interest in using IVR to identify personal triggers in context, discuss emotional responses while being immersed, and repeatedly rehearse refusal skills or alternative actions for temporary clinical leave.

In the second study, an existing IVR cue reactivity environment was used to explore the feasibility and acceptability of practicing coping strategies for nicotine craving, alongside descriptive craving assessments. All participants reported that the IVR elicited nicotine craving, and most were able to complete the procedure. This suggests that the use of IVR was feasible in an inpatient MBID setting, when therapist support was available. Participants perceived several coping strategies as helpful, which were related to distraction (eg, games and virtual pets), relaxation (eg, mindfulness and breathing exercises), and physical activity (eg, sport and walking the dog). Descriptively, nicotine craving tended to increase during cue exposure and decrease during the tutorial and coping phases. Notably, participants differed in how they experienced the specific IVR scenarios, and some required additional support due to anxiety or unfamiliarity with IVR. For example, one participant described a virtual riverside environment as triggering for nicotine craving due to personal associations with alcohol use (“I live close to the IJssel [Dutch river] myself and that was a very triggering place for me last summer, because automatically people sit there to drink alcohol” [S04]), whereas other participants experienced similar scenarios as craving reducing. This illustrates that the subjective meaning of IVR scenarios can vary substantially between individuals and that certain environments may evoke unintended craving responses depending on personal history.

Taken together, these findings suggest that IVR may provide a structured and experiential format for identifying high-risk situations and rehearsing coping responses in context for individuals with MBID. This is particularly relevant given the barriers in MBID treatment, including difficulties with abstract reflection and transfer of coping skills to everyday environments [2,8].

Interpretation and Comparison With Prior Work

Participants in Study 1 identified different high-risk alcohol situations such as supermarkets, home settings, social gatherings, and public spaces. These findings are consistent with previous research on triggers in AUD, which has highlighted the role of environmental cues such as bars and stores in eliciting cravings [21,33]. However, participants in the present study frequently described these environments in combination with social influences (eg, peer pressure and interpersonal conflict) and affective states (eg, tension, negative affect, and distress) as triggers for alcohol craving. For example, in supermarkets, alcohol exposure was described as stressful and confrontational due to advertisements and visibility of alcohol products. Social gatherings were linked to invitations and pressure to drink. In the home setting, alcohol use seemed to be described as embedded in a habitual sequence of actions, such as coming home, sitting on the couch, watching football, and then drinking.

These findings indicate that alcohol craving in this MBID sample was experienced as embedded in daily routines and interpersonal situations, rather than triggered by exposure to environmental stimuli alone. This aligns with broader conceptualizations of craving as context-dependent while being influenced by affective and social processes [33]. In this study, participants described complex situations in which contextual cues, emotions, and social interactions were closely intertwined. For individuals with MBID, who often find it difficult to analyze and describe their everyday risk situations [2,8], addressing such interconnected triggers in a traditional CBT session can be challenging. CBT typically relies on retrospective discussion and functional analysis of high-risk situations. This requires patients to reconstruct the situation, identify the links between context, emotion, and behavior and consider alternative responses. Within this context, IVR may offer a complementary way to examine and rehearse high-risk situations in a more concrete and structured way.

While most IVR cue reactivity research operationalizes craving through predefined substance-use environments, such as bars or public venues [10,17,18], the present study identified high-risk situations and triggers for alcohol craving in patients with MBID through a bottom-up approach derived directly via interviews with patients. The situations described by participants were often routine and home-based and embedded in everyday activities rather than limited to prototypical drinking locations. Using these patient-derived situations as a starting point when developing IVR scenarios may increase the practical relevance of IVR within MBID inpatient treatment.

In the second study, participants explored several coping strategies to reduce nicotine craving in IVR. All patients reported that the IVR environment induced nicotine craving, confirming its ecological validity, consistent with earlier findings [13]. Interestingly, nicotine craving decreased during the tutorial phase, which contrasts with previous results that showed increased nicotine craving during immersion [13]. One possible explanation for this difference is that the gamified tutorial required sustained attention and functioned as a distraction, thereby reducing nicotine craving. This observation suggests that the structure and content of the tutorial phase may influence craving responses and should therefore be considered carefully when designing IVR protocols.

Participants perceived coping strategies that were embedded within IVR as helpful, particularly those that involved concrete actions such as interacting with virtual animals or engaging in games. This suggests that including active coping components within IVR may be important, rather than relying on cue exposure alone [22,26]. However, participants differed in how they experienced certain environments, which highlights the need for careful scenario selection and therapist guidance. The riverside example illustrates that environments intended to be calming may evoke craving if they are associated with prior substance use experiences. This underscores the importance of assessing personal associations and monitoring tolerability when integrating IVR into clinical care.

Implications for the Development of an IVR-CBT for Patients With MBID

The findings from both studies provide practical starting points for the development of IVR-supported CBT elements within MBID SUD treatment. The present studies identified high-risk situations and coping strategies that patients themselves considered as relevant within inpatient MBID treatment and demonstrated that practicing coping skills within IVR was feasible and acceptable when therapist support was available. Participants also described treatment-related goals, such as discussing feelings with therapists during IVR sessions, practicing refusal skills, and learning to manage craving-related distress. These goals align with CBT mechanisms such as functional analysis and coping skills training [34], as well as with MBID-adapted CBT protocols that are used within Dutch inpatient treatment settings at the time of this writing [9].

Although clinical effectiveness was not evaluated, the descriptive reductions in craving during the coping phases suggest that CBT-based coping strategies, including self-control techniques tailored to the needs of patients with MBID, can be operationalized within IVR environments. The possibility to simulate socially and emotionally complex situations in a structured and controlled setting may allow for repeated rehearsal, which can be difficult to stimulate in traditional therapy but can be practiced safely and repeatedly in IVR. Prior studies have shown that IVR is effective at establishing cue reactivity by simulating real-life scenarios related to substance use. However, many applications focused primarily on exposure to SUD-related cues, without embedding active coping skill training or other therapeutic elements that are essential for behavioral change [35]. Integrating coping rehearsal directly within IVR may help to address this limitation by combining immersive exposure with the immediate practice of coping strategies.

Based on the findings from both studies, several design and implementation considerations for developing IVR-CBT interventions (ie, trigger-coping scenarios) can be identified. First, IVR environments may be useful for supporting two fundamental CBT objectives: (1) identification of high-risk situations and triggers (CBT: stimulus control) and (2) coping with trigger-induced craving (CBT: stimulus response prevention) [36]. IVR may function as a complementary modality within existing CBT protocols by enabling in-context rehearsal of skills that are otherwise discussed retrospectively. In doing so, a structured IVR-CBT framework may be developed that systematically links CBT objectives to certain IVR training modules with risk-coping scenarios, grounded in both CBT theory and immersive learning design. Stimulus control could be addressed through specific IVR trigger-assessment modules, in which patients, for instance, identify, label, and rate high-risk situations or triggers via simplified interfaces and real-time feedback tools via either the IVR or the therapist. Once patients can recognize and assess their high-risk situations and triggers, the next step would involve training them to actively manage their responses, thereby moving from stimulus control to stimulus-response prevention. The transition from stimulus control to stimulus-response prevention can be supported by an IVR-CBT framework with a staged approach that aligns technological affordances with a pedagogical learning design, as recommended by [37], by sequencing skill acquisition through concrete, repetitive, and context-specific activities.

Moreover, given the variability in individual trigger experiences observed in this study, IVR systems may benefit from allowing flexibility in scenario selection and coping options. Personalization through therapist-patient goal setting [37] and the use of customized scenarios that are based on each patient's individual triggers and coping needs [38] might enhance clinical relevance. For instance, patients presenting with predominantly social triggers can, for instance, engage in peer-pressure simulations involving assertive refusal training, while patients with predominantly environmental triggers (eg, being in a bar) may work within location-based scenarios that focus more on stimulus control and rehearsal of coping strategies (eg, going for a walk). However, it is still uncertain whether individualized tailoring improves outcomes when compared to standardized IVR modules, as this still requires empirical evaluation.

Furthermore, IVR content may benefit from alignment with individualized high-risk situations and trigger profiles systematically linked to personalized coping strategies, while keeping a balance between personalized IVRs and standardized treatments [39]. It is important that researchers distinguish therapeutic mechanisms from educational ones, as skill learning in IVR may occur even in the absence of immediate relief effects, which are typically associated with real-world coping. Therefore, future studies should not only evaluate whether patients can learn coping strategies in IVR but also how these strategies generalize to behavior outside of IVR. Finally, the development of IVR-CBT protocols may benefit from interdisciplinary collaboration to address clinical, technological, and implementation considerations, including questions related to intensity and dosage. Future research could contribute to the development and empirical evaluation of a CBT-informed framework for IVR interventions that links identified triggers to coping strategies across structured learning stages. In addition, further studies should examine personalization capabilities, implementation barriers, and acceptability of IVR-CBT across broader MBID populations and diverse treatment settings.

Limitations

Several limitations should be considered. First, both studies included small convenience samples recruited from a single clinic; therefore, limiting the extent to which the results can be generalized to other settings or MBID populations. Our convenience sampling might have over-represented individuals with MBID who were comparatively stable, motivated, and comfortable with technology since participation in the studies was voluntary and patients with severe psychiatric instability were excluded, resulting in selection bias. As a result, our findings may not fully apply to the perspectives and needs of individuals with higher levels of psychiatric complexity or lower technological literacy. Second, the 2 studies focused on different substances and different therapeutic targets. While AUD and ND may share some features, they may also differ in contextual triggers, behavioral patterns, and treatment mechanisms; therefore, the findings should be interpreted within each specific substance context. While overlapping processes such as cue

reactivity and coping rehearsal may be relevant across SUDs, the specific triggers and coping elements that were identified in this work are substance-specific and design-oriented. In addition, the studies were exploratory and design-oriented, thereby not assessing clinical effectiveness, long-term outcomes, or the generalization of learned coping strategies beyond the IVR context. Third, the data were collected verbally by nurses (in training to become specialists) to resemble a common treatment setting. However, this might have increased social desirability bias (eg, see contrary craving effects during the tutorial phase), though paper-based assessments appear too complex for our group. Fourth, the interactions within the IVR were limited and of short duration due to the explorative nature of our study. This might have restricted the patient's opportunity to fully practice coping responses extensively and may have limited the extent to which craving reduction could be observed. Fifth, it is important to note that we demonstrated and explored coping skills by using a pre-existing IVR system. This may have caused confirmation bias because participants' given responses may have been influenced by the available specific examples and functionalities that were presented, which may have limited the identification of additional coping strategies. Instead, our explorative research aimed to generate or understand how IVR can be integrated into current CBT treatment in patients with MBID and SUD. Finally, participants might have participated in prior studies by our group, which could influence the data collected.

Conclusions

IVR-supported CBT elements appear feasible and acceptable in an inpatient MBID setting when appropriate support is available. The present studies provide concrete, patient-derived design insights into alcohol-related high-risk situations and nicotine-related coping elements that can be embedded in IVR. The findings of these studies suggest that IVR may help to reduce barriers that are associated with abstract verbal reflection by enabling in-context identification of triggers and repeated rehearsal of coping responses within a controlled environment. However, IVR environments may activate personally learned substance-use associations that differ between individuals. Therefore, careful scenario selection, real-time craving monitoring, and therapist guidance seem to be necessary to prevent unintended increases in craving.

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Data Availability

The datasets generated and analyzed during the current study are not publicly available because they contain sensitive qualitative and clinical data from a vulnerable patient population. Data may be available from the corresponding author on reasonable request, subject to institutional and ethical approval.

Authors' Contributions

Conceptualization: SM, SL
Investigation: SL
Formal Analysis: SL
Writing – Original Draft: SM, SL
Writing – Review & Editing: SM, SL, HK, SK, JVN, DH, RK
Supervision: DH, RK, JVN
All authors read and approved the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Semistructured interview on alcohol-related high-risk situations and triggers for immersive virtual reality-cognitive behavioral therapy (IVR-CBT).

[DOCX File, 17 KB - xr_v3i1e82601_app1.docx]

Multimedia Appendix 2
Semistructured interview on coping strategies to reduce nicotine craving in immersive virtual reality (IVR).
[DOCX File, 16 KB - xr_v3i1e82601_app2.docx]

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Abbreviations

AUD: alcohol use disorder
BIF: borderline intellectual functioning
CBT: cognitive behavioral therapy
FTND: Fagerström Test for Nicotine Dependence
HMD: head-mounted display
IVR: immersive virtual reality
MBID : mild to borderline intellectual disability
MID: mild intellectual disability
ND: nicotine dependence
QSU-Brief: Questionnaire of Smoking Urges-Brief
SUD: substance use disorder
VAS: Visual Analogue Scale
VE: virtual environment
VR: virtual reality
VRET: virtual reality exposure therapy

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Brief Virtual Reality and Mixed Reality Mindfulness Breathing Exercise for Emotional Well-Being and Cognitive Functions in University Students: Within-Subjects Experimental Design Study

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Abstract

Background: Mindfulness has been shown to enhance emotional well-being and cognitive performance, yet much of this evidence stems from interventions requiring prolonged practice, making them time-consuming and less accessible. Recent studies suggest that brief mindfulness sessions may also yield positive outcomes, but the effectiveness of such interventions in virtual reality (VR) and mixed reality (MR) remains underexplored.

Objective: This study investigates the effects of brief mindfulness breathing exercises delivered through VR and MR on attentional and emotional restoration and self-control capacity.

Methods: Using a within-subjects experimental design, 102 undergraduate participants (n=83, 81.4% female; mean age 20.87, SD 1.89) completed a brief (approximately 15 min) VR and MR mindfulness breathing intervention delivered via a head-mounted display and a duration-matched mind-wandering audio control condition. Participants were undergraduates recruited via convenience sampling from psychology courses in a local university in Singapore. These conditions were separated by a 1-week washout period. Emotional well-being and self-control capacity were measured at baseline and post treatment, using self-report measures, whereas working memory capacity was measured at both time points, using operation span at baseline and rotation span post treatment.

Results: Repeated-measures ANOVAs (α=.05) indicated that VR and MR mindfulness breathing conditions significantly enhanced positive affect (P<.001, η_p^2=0.366), reduced negative affect (P<.001, η_p^2=0.279), and improved self-control capacity (P<.001, η_p^2=0.219), compared with the mind-wandering control condition. In contrast, no significant differences were observed for working memory, and Bayesian analyses provided moderate evidence in support of the null hypothesis for both the main effect of condition and the time×condition interaction (BF_{01}=7.42 and BF_{01}=5.55, respectively). Participants reported significantly greater absorption in the VR and MR conditions than in the control condition (Cohen's d=−1.61, 95% CI −1.91 to −1.32).

Conclusions: These findings suggest that a brief VR and MR mindfulness breathing exercise improves emotional well-being and self-control capacity relative to a mind-wandering control but does not yield short-term benefits for working memory. In contrast to existing studies that typically emphasize stress reduction or rely on multisession digital interventions, this study highlights that a single brief VR or MR session can enhance key emotional and self-regulatory outcomes. As such, these results underscore the potential of VR and MR mindfulness interventions as scalable and accessible tools for promoting mental well-being, while also pointing to the need for further research to optimize their cognitive impact.

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KEYWORDS

mindfulness; virtual reality; mixed reality; emotional well-being; working memory capacity

Introduction

Background

Mindfulness, defined as the enhanced awareness of moment-to-moment experiences, where one intentionally attends to their thoughts, emotions, and bodily sensations in a nonjudgmental and accepting manner [1,2], has consistently been shown to provide wide-ranging psychological benefits across both general [3,4] and clinical populations [5,6]. Evidence from numerous studies indicates that mindfulness-based interventions are associated with a range of positive outcomes related to well-being, including higher levels of life satisfaction [7-9], vitality [7,10], optimism [11,12], pleasant affect [7,13,14], improved emotional processing [15,16], and emotional

regulation [17-19]. Furthermore, these practices have been shown to effectively reduce depressive symptoms [7], stress [10,20,21], anxiety [22,23], and emotional reactivity [24-26]. These benefits arise not from suppressing or altering experiences, but from focusing on how individuals interpret their present-moment experiences [27,28]. When individuals perceive their thoughts and feelings as transient mental events that are impermanent in nature, they can reframe negative thoughts and decrease emotional reactivity, fostering a deeper sense of calm and well-being [29-31].

Beyond its mental health benefits, research has increasingly shown that mindfulness enhances cognitive performance [32-35] and is closely associated with improvements in executive functions, including inhibitory control, task-switching, and working memory [36-38]. The strong link between mindfulness and executive functions is theoretically well-grounded, as both rely on maintained attention and cognitive monitoring, indicating an overlap in their underlying cognitive mechanisms [39-41]. By fostering a relaxed mental state that promotes focused attention, mindfulness optimizes resource allocation and reduces mind-wandering, thereby improving cognitive performance [42,43].

In addition to cognitive benefits outlined above, mindfulness is closely linked to self-control. According to self-regulation theory [44], self-control operates as a limited resource that can be depleted under stressful and cognitively demanding conditions and replenished under restorative conditions. Cognitively demanding tasks require long-term executive control, such as maintaining attentional focus on goal-relevant information, suppressing distractions or impulses, and managing competing mental representations, and draw upon limited self-regulatory resources and temporarily reduce subsequent cognitive and emotional control capacity [45]. In contrast, restorative conditions are states or environments that facilitate the recovery of these depleted resources, including exposure to natural environments that promote attentional restoration, engagement in relaxation or mindfulness practices, or periods of rest that foster emotional rebalancing and cognitive recovery. When this resource is depleted, individuals may struggle with goal-directed behavior, impulse control, and regulation. A possible mechanism underlying this effect is that mindfulness enhances two fundamental self-control processes: (1) emotion regulation [17-19] and (2) attention regulation [33,46,47], both of which are crucial for maintaining self-regulatory capacity [44,48]. By enhancing these regulatory capacities, mindfulness provides a potential mechanism through which self-control resources can be replenished, thereby supporting long-term self-regulatory functioning.

Despite accumulating evidence on the positive outcomes of mindfulness on attentional and emotional restoration and self-control capacity, most findings are drawn from intensive programs, which typically span several weeks, requiring participants to engage in regular and often prolonged sessions under expert guidance [49]. Mindfulness-based stress reduction (MBSR) and mindfulness-based cognitive therapy are among the most pervasive and well-established interventions, with participants practicing mindfulness for up to 45 minutes daily and attending weekly group sessions that are 8 weeks long [2,50]. Specifically, 1 study demonstrated that MBSR is associated with reduced stress and enhanced psychological well-being [2], evidenced by improvements in emotional regulation, decreases in anxiety, and increases in life satisfaction among participants. Similar findings have been reported for other intensive mindfulness interventions. For example, a study found that participants who underwent a 1-month intensive mindfulness training reported significant reductions in anxiety and improvements in subjective well-being and self-compassion compared with a waitlist control group [51]. Additionally, another study found that novice meditators who participated in a 10-day intensive mindfulness training retreat demonstrated significant improvements in self-reported mindfulness, depressive symptoms, rumination, working memory, and maintained attention, relative to a comparison group who did not undergo any mindfulness training [32]. Generally, studies have highlighted the efficacy of intensive mindfulness interventions in improving well-being [52,53] and cognitive performance [54,55] compared with control conditions. Mindfulness fosters emotional regulation by increasing present-moment awareness and promoting acceptance of thoughts and feelings. According to the monitor and acceptance theory [56], mindfulness operates through two complementary mechanisms: (1) attention monitoring enhances awareness of moment-to-moment experiences, and (2) acceptance fosters a nonjudgmental and open stance toward these experiences. The interaction between these processes facilitates adaptive emotion regulation by allowing individuals to observe internal states without reacting impulsively.

Despite strong support for intensive mindfulness intervention, research on brief mindfulness has yielded mixed findings. On one hand, some studies report improvements in affect [57], reduced emotional reactivity, and enhanced attentional control [58,59]. Supporting this perspective, 1 study found that a single 15-minute mindfulness session significantly improved positive affect (PA) and reduced emotional reactivity in response to emotionally charged stimuli [60], highlighting the immediate benefits of mindfulness for emotional regulation. Similarly, another study showed that a single 15-minute brief mindfulness session could enhance attentional control by reducing mind-wandering during cognitive tasks [42], suggesting a notable impact on cognitive focus. While mindfulness has been associated with reduced emotional reactivity, it is important to note that reactivity itself is not inherently maladaptive. Emotional reactivity serves adaptive functions, which allow individuals to respond appropriately to meaningful positive or negative events. Excessive dampening of emotional responses, particularly to positive experiences, may reflect emotional blunting or reduced reward sensitivity, which can undermine well-being. Rather than eliminating reactivity, mindfulness promotes adaptive regulation, fostering flexibility to modulate emotions in a context-sensitive manner.

However, the outcomes of brief mindfulness practices are not always positive. Specifically, 1 study observed that a 15-minute mindfulness meditation did not significantly reduce negative affect (NA) relative to active control (guided progressive muscle relaxation training) and passive control (watching a TED Talks video) groups [61]. Likewise, another study found no

improvement in working memory capacity following a 15-minute mindfulness breathing exercise in 2 high-powered studies [62]. These mixed findings highlight both the promise and limitations of brief mindfulness and underscore the need for approaches that can deepen engagement without imposing the burden of long-term practice [63,64]. One potential explanation for these inconsistencies is that brief mindfulness exercises may lack the long-term engagement and depth provided by intensive practices, such as MBSR and mindfulness-based cognitive therapy, which are essential for achieving optimal outcomes [49,65]. To address this limitation, recent technological advancements in virtual reality (VR) and mixed reality (MR) may offer promising solutions to enhance brief mindfulness practices.

VR and MR technologies provide avenues for enriching mindfulness practices by offering immersive environments that foster greater focus and engagement [66-68]. For example, one study found that VR provides an immersive environment that may reduce typical barriers to mindfulness practice by increasing engagement and reducing distraction [66]. Another study reported that integrating mindfulness with immersive VR shows promise for improving mood, attention, and engagement [67]. Finally, another study demonstrated that immersive VR conditions can produce greater mindfulness and stress-reduction effects than conventional mindfulness formats in some samples [68]. VR, in particular, provides controlled multisensory environments that simulate natural settings and promote focus [69,70]. Additionally, VR provides multisensory experiences that allow users to interact with virtual natural environments, helping them to disconnect from everyday stressors and deepen their mindfulness practice [71]. Meanwhile, MR, which integrates real and virtual elements, can further enhance mindfulness training by providing real-time feedback and increasing interactivity, which may further boost engagement [72,73]. Recent studies have explored the potential benefits of VR-based mindfulness, showing associations with reduced negative emotions [69,74-76], increased positive emotional states [66,77], and cognitive improvements in attention and working memory [46,78]. Yet, findings have not been entirely consistent, with some studies reporting significant effects on either PA or NA but not both [66,79].

Despite the growing body of research on VR and MR mindfulness interventions, important gaps remain, particularly concerning their effectiveness in brief applications and whether they provide emotional and cognitive benefits comparable with those of more intensive mindfulness practices. Most evidence supporting the cognitive benefits of VR-based mindfulness comes from studies involving multiple sessions, leaving uncertainty about whether shorter interventions yield similar positive outcomes [46,78]. For example, 2 separate studies reported having 8 sessions of the VR mindfulness intervention [46,78]. Moreover, many of these studies face methodological limitations, such as small sample sizes [66] and inadequate or inconsistent control groups [80,81], which constrain the robustness and generalizability of their findings. Research on MR-based mindfulness remains even more limited, despite its potential for enhanced interactivity [73]. These gaps are increasingly salient given recent technological developments, such as the Meta Quest 3 and Apple Vision Pro, which support both VR and MR modes. Emerging mindfulness applications also blend these modalities by embedding virtual cues within real environments or transitioning into full immersion when deeper focus is needed [82]. Thus, addressing these gaps through further empirical investigations is crucial to establishing the efficacy of brief VR and MR mindfulness interventions in enhancing emotional well-being and cognitive functioning and to determining their potential for scalable implementation across diverse real-world settings.

This Study

This study examined whether a brief mindfulness breathing exercise delivered via VR and MR can enhance emotional restoration, attentional functioning, and self-control capacity relative to a mind-wandering control condition. Using a within-subjects experimental design, participants completed both VR and MR mindfulness breathing exercises as well as a mind-wandering audio condition where participants were instructed to let their mind wander freely with no mindfulness advice provided, with a 1-week washout period between conditions to minimize carryover effects. We hypothesized that a brief mindfulness breathing intervention in VR and MR would lead to significant improvements in attentional and emotional restoration and self-control capacity compared with the mind-wandering control condition. Emotional and self-regulatory outcomes were assessed using standardized self-report measures, while working memory capacity was assessed using 2 well-established complex span tasks—the operation span (OSpan) task and the rotation span (RotSpan) task. These tasks were chosen for their strong validity and sensitivity to within-person changes in attentional functioning [83]. Repeated-measures ANOVA was used to examine condition-based differences across emotional, cognitive, and self-regulatory domains.

In this study, we selected PA and NA as immediate, subjective indicators of emotional well-being to capture participants' affective states following mindfulness and VR or MR interventions. Although mindfulness has been shown to enhance several executive functions, including inhibitory control, task-switching, and working memory, we focused on working memory as it represents a central component of executive function and reflects the capacity to maintain goal-relevant information during mindful attention [36]. Previous research suggests that mindfulness training can improve working memory capacity by reducing mind-wandering and enhancing attentional stability, making it an appropriate measure for detecting short-term cognitive changes in a brief intervention [42]. We also conceptualized self-control within the limited resource framework of self-regulation, where momentary acts of regulation, attention control, or emotional management draw from a finite pool of control resources [84]. Because self-control sits at the intersection of executive control and emotional regulation [44], it serves as a meaningful link between our cognitive outcome (working memory) and affective outcomes (PA and NA). Hence, this study aimed to examine the effects of a brief (approximately 15 min) VR and MR mindfulness breathing exercise on attentional and emotional restoration and

self-control capacity, compared with a mind-wandering control condition.

Methods

Transparency and Openness

This study's design and analysis plans were preregistered. The details of the preregistration are available on AsPredicted [85]. All preregistration documents and supplementary materials are publicly available on ResearchBox #3410 [86]. The study was reported in accordance with the APA Journal Article Reporting Standards (JARS) [87]. Frequentist analyses were conducted using IBM SPSS 29.0.1.0 [88], while Bayesian analyses were conducted using JASP version 0.17.3 [89] to examine evidence for null effects. The extent and pattern of missing data were examined across all primary outcome variables (PA, NA, self-control capacity, and working memory capacity) using SPSS Missing Value Analysis.

Participants

A total of 113 participants were recruited from a local university in Singapore. All participants were psychology undergraduates recruited using convenience sampling, and they received course credits for their participation. Each participant completed 2 counterbalanced sessions. Data from 11 participants were excluded from the analyses due to noncompliance with task instructions or insufficient immersion during either the experimental or control conditions, as indicated by experimenter observation. These participants appeared distracted or failed to engage consistently with the instructions. Specifically, 1 participant, who reported having dyslexia, was removed due to the potential impact of dyslexia on cognitive performance in the RotSpan task. Additionally, 1 participant encountered a technical error, and 9 participants failed to comply with study instructions. This resulted in a final analytic sample of 102 participants. Participant recruitment, eligibility screening, exclusions, assignment, and the final analyzed sample are summarized in a JARS-adapted flowchart in Figure 1. The demographic characteristics of participants are provided in Table 1.

Figure 1. Journal Article Reporting Standards–adapted participant flowchart depicting recruitment, eligibility screening, exclusions, assignment, and final analyzed sample in a within-subjects experiment.

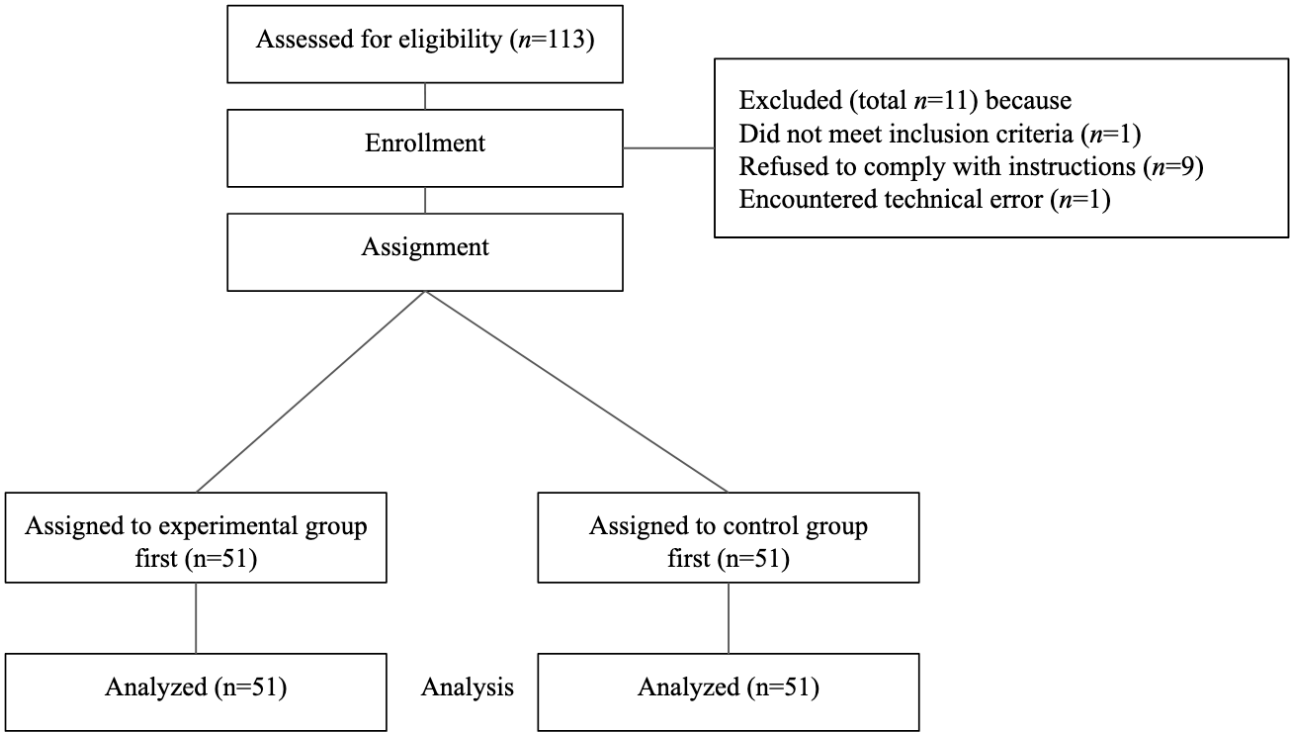


Table . Demographic characteristics of the sample (N=102) in a within-subjects experiment comparing brief VR[a] and MR[b] mindfulness breathing and a mind-wandering control.

Characteristic	Value	Observed range
Sex (female), n (%)	83 (81.4)	—[c]
Ethnicity (Chinese), n (%)	78 (76.5)	—
Age (y), mean (SD)	20.87 (1.89)	18 - 30
Monthly household income[d], mean (SD)	3.70 (1.49)	1 - 6
Subjective socioeconomic status[e], mean (SD)	6.30 (1.42)	2 - 9

[a]VR: virtual reality.

[b]MR: mixed reality.

[c]Not applicable.

[d]Participants rated their monthly household income on a 6-point scale ranging from less than SGD 2000 to more than SGD 20,000; (1) less than SGD 2000 (US $1570.38); (2) SGD 2000-5999 (US $1570.38-US $4710.34); (3) SGD 6000-9999 (US $4711.13-US $7851.10); (4) SGD 10,000-14,999 (US $7851.88- US $11,777.04); (5) SGD 15,000-19,999 (US $11,777.82-US $15,702.98); (6) more than SGD 20,000 (US $15,703.76).

[e]Participants rated their subjective socioeconomic status using the MacArthur Scale of Subjective Social Status [90], a ladder which represented where people stood in society, and participants had to estimate where one stood on the ladder.

The sample size of this study was determined using an a priori analysis in G*Power 3.1.9.7 [91] to ensure that the study was designed to meet the minimum sample size needed to detect an effect with 80% statistical power. Based on a medium effect size of f=0.25, an α level of .05, and at least 80% power (1–β), the analysis indicated that a minimum of 34 participants would be needed. Additionally, to ensure sufficient statistical power, a post hoc sensitivity power analysis was conducted using the same G*Power settings. This analysis indicated that with our final sample size (n=102), the study was adequately powered to detect the time×condition interaction effects specified by the study design as small as f=0.14 (equivalent to η_p^2=0.019), which represents a small-to-medium effect size. No missing values were observed for any of the primary outcome variables.

Ethical Considerations

All procedures were approved by the university's Institutional Review Board (IRB-24 - 119-A087-M2(1124)) and complied with its ethical guidelines. Participants were informed about the study aims, procedures, potential risks, and their right to withdraw at any time without penalty and provided written informed consent before the first session. To protect privacy and retain confidentiality, participants were identified only by unique identification codes. No personally identifiable information was stored with the research data. All analyses were conducted using deidentified datasets, with data access restricted to the research team. Participants received course credit in exchange for completing both study sessions. No images included in the manuscript or supplementary materials allow for the identification of individual participants. Informed consent was obtained from the individual depicted in Figure 2 for the use of their image in this publication.

Figure 2. Participant wearing a Meta Quest 3 VR headset and hand controllers during the virtual reality and mixed reality mindfulness breathing condition in a within-subjects experiment.

Study Design

This study used a 2 (condition: VR+MR mindfulness breathing vs mind-wandering)×2 (time: baseline vs postintervention) within-subjects experimental design. The within-subjects approach was chosen to control for interpersonal variability, thereby reducing errors associated with individual differences and enhancing the ability to detect true differences between conditions, ultimately increasing statistical power. All participants experienced both the experimental and control conditions. In the experimental condition, participants engaged in a brief VR and MR mindfulness breathing intervention that lasted approximately 15 minutes. In the control condition, they engaged in a mind-wandering audio that lasted approximately 15 minutes. The order of conditions was counterbalanced, with half of the participants completing the experimental condition first and the other half completing the control condition first. To mitigate potential carry-over effects, sessions were separated by a 1-week interval, which served as a washout period to allow any practice or residual effects from the first session to subside [92,93]. Participants underwent random assignment through Qualtrics to establish the sequence in which they experienced the 2 different conditions.

Materials

Emotional Well-Being

State affect was measured using the 18-item Circumplex Model of Affect Scale [94], which evaluates emotional states along 2 independent dimensions—PA and NA. Participants rated their current emotional state on a 5-point Likert scale (1=*Not at all*, 5=*Extremely*) in response to the question, “Overall, how do you feel right now?” The PA scale includes 9 items, that is, energetic, enthusiastic, excited, happy, cheerful, pleasant, calm, content, and relaxed. The NA scale includes 9 items, that is, angry, hostile, irritable, nervous, anxious, tense, dejected, sad, and unhappy. Higher scores indicated greater agreement with the respective states. The PA scale demonstrated good internal consistency at baseline (α_{pre}=.90), after the VR or MR mindfulness condition (α_{post}=.93), and after the mind-wandering control condition (α_{post}=.91). The NA scale demonstrated good internal consistency at baseline (α_{pre}=.90), after the VR or MR mindfulness condition (α_{post}=.88), and after the mind-wandering control condition (α_{post}=.86).

Self-Control Capacity

Self-control capacity was measured using the 5-item Brief State Self-Control Capacity Scale [95]. Participants rated their agreement with each statement (eg, I feel drained now; I feel calm and rational now) on a 7-point Likert scale (1=*Very untrue of me*, 7=*Very true of me*), in response to the question, “Overall, how do you feel right now?” Higher scores indicated greater agreement with the respective states. The scale demonstrated good internal consistency at baseline (α_{pre}=.75), after the VR or MR mindfulness condition (α_{post}=.74), and after the mind-wandering control condition (α_{post}=.78).

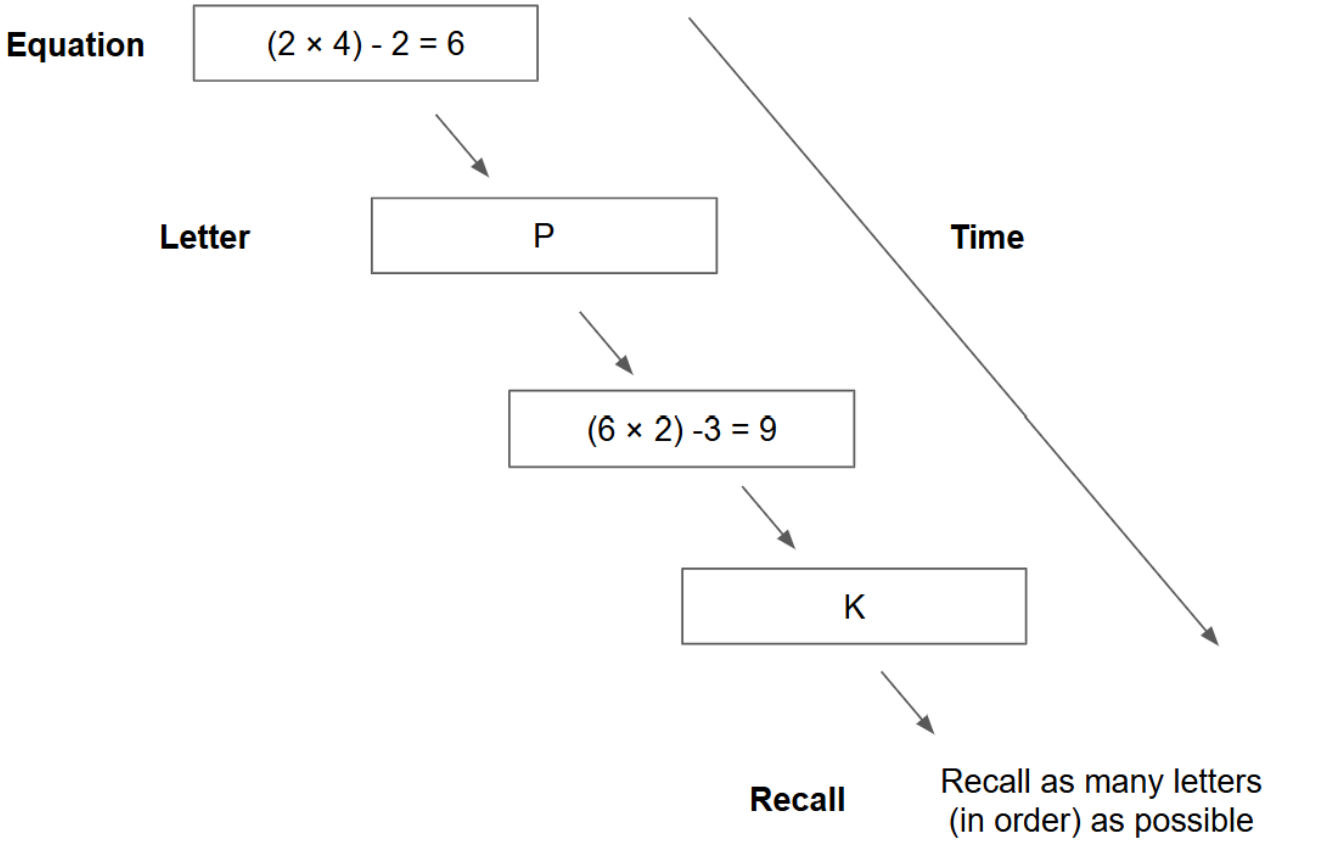
Working Memory Tasks

Working memory capacity was measured using 2 established shortened complex span tasks—OSpan task and the RotSpan task, administered via E-Prime 3.0 [96]. These tasks are accessible on the Attention & Working Memory Lab website [97]. These tasks were selected as performance on complex span tasks has been shown to be malleable and sensitive to experimental manipulation such as training instructions [83]. Although the OSpan (verbal) and RotSpan (spatial) tasks differ in stimulus modality, both tasks are validated measures of domain-general working memory capacity and share the same dual-task structure, which makes them comparable indicators of working memory capacity.

In both tasks, participants were required to memorize a series of items (eg, letters or arrows) while performing interspersed distractor tasks (eg, solving math equations or identifying rotated letters). The number of items to be memorized varied per trial, ranging from 2 to 7, with each sequence length appearing 3 times in a randomized order. To minimize the likelihood of rehearsing memorized items during the distractor task, participants were required to respond to the distractor tasks at a steady pace. Before beginning the main trials, participants completed a practice round for each task to ensure they fully understood the instructions.

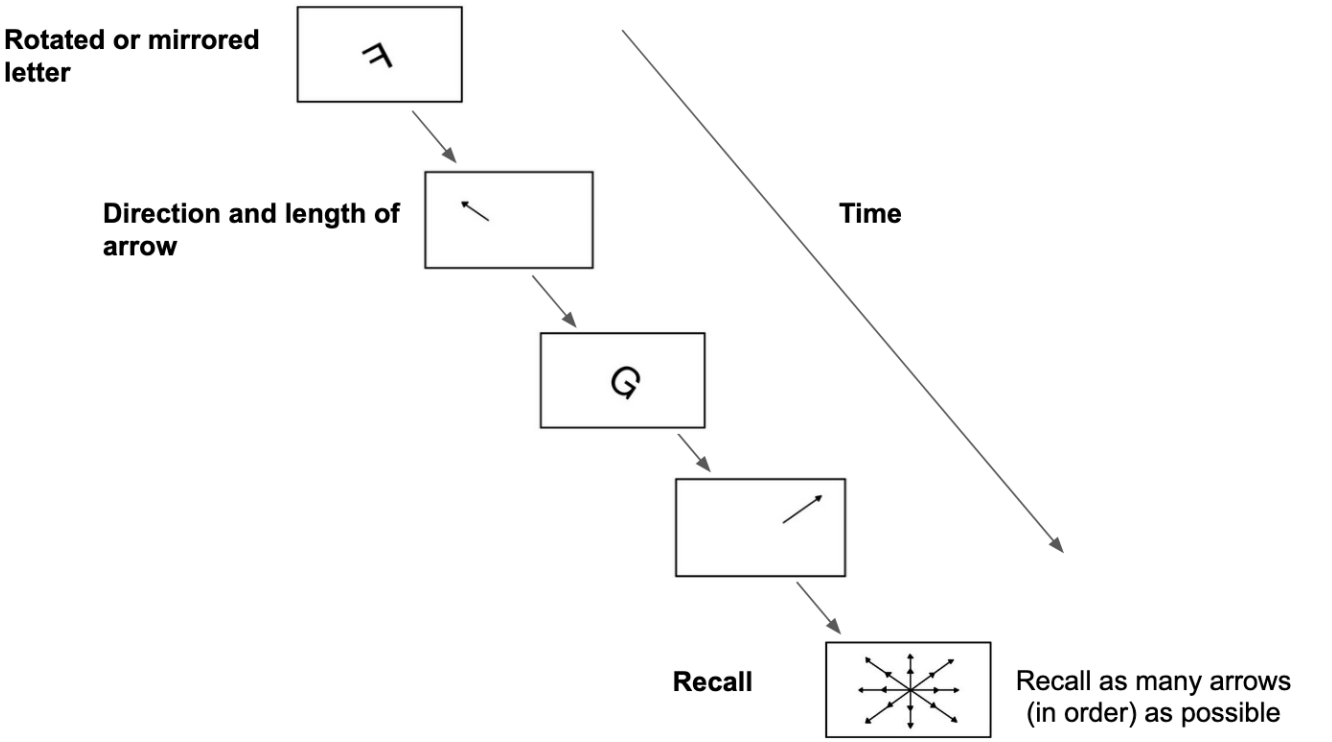
Baseline working memory capacity was assessed using the OSpan task. In this task, participants solved mathematical equations while simultaneously memorizing a sequence of letters for later recall (Figure 3). The letters served as items to be remembered, and the math problems acted as distractors. During each trial, participants first solved a math equation and then viewed a letter. This math-letter sequence was repeated between 3 and 7 times, with the number of repetitions varying unpredictably across trials. At the end of each trial, participants were asked to recall the letters in the correct order. Performance was scored using the partial credit unit method, which is based on the number of correctly recalled letters divided by the total number of letters presented within each trial and then averaged across all trials [83]. Each participant completed 2 blocks of trials.

Figure 3. Operation span task flow to assess working memory capacity in an experimental within-subjects trial in undergraduate students in Singapore.



Posttreatment working memory capacity was measured using the RotSpan task, which is similar to the OSpan task but involves different items and operations. In this task, participants judged whether a rotated letter was correctly oriented or mirrored while also memorizing a sequence of arrows, each varying in direction and length (Figure 4). The arrows served as items to be remembered, and the rotated letters acted as distractors. During each trial, participants first judged the orientation of a rotated letter and then viewed an arrow. The rotation-arrow sequence was repeated 2-5 times, with the number of repetitions varying across trials. After each sequence, participants were required to recall the arrows in the correct order. Each participant completed 2 blocks of trials. The partial credit unit score was used to index performance [83].

Figure 4. Rotation span task flow to assess working memory capacity in an experimental within-subjects trial in undergraduate students in Singapore.



Brief VR and MR Mindfulness Intervention

In the VR and MR mindfulness breathing condition, participants engaged in a mindfulness breathing exercise that lasted approximately 15 minutes using the Meta Quest 3 VR headset (Figure 2). Before the mindfulness breathing exercise, the experimenter instructed participants to prepare and explained how to use the controllers for 2 specific functions, which were used to navigate the virtual environments. Participants were informed that their VR screen would be shared on an external monitor (but not recorded) and reminded to follow the guided audio throughout the exercise. The VR and MR mindfulness breathing condition was administered through the Headspace XR app. Headspace XR offers both virtual and MR experiences, featuring mood-enhancing games, personalized guided meditations, and exercises designed to help users improve their mind-body connection through movement and breathing techniques. For this study, participants were tasked to engage in 3 mindfulness breathing activities within Headspace XR.

The first activity, "Take a Beat Portal," adopts a technique known as "box breathing," which takes place in an MR setting (Figure 5). In this activity, participants would first find an object or feature in the room that is shaped in a square. Then, they were instructed by the audio to draw a box-shaped virtual overlay that they would be using for the breathing exercise. Once the shape is drawn, participants complete three sets of four controlled breathing cycles. The guided audio included instructions, such as "Inhaling…feeling your chest and stomach expanding [...] Holding…feeling the breath in your body [...] Exhale… feeling the release of any tension [...] Holding… before the next breath." This entire activity lasts approximately 5 minutes.

Figure 5. Screenshots of the three mindfulness breathing activities used in the virtual reality and mixed reality conditions. The 3 panels depict the mindfulness breathing environments used in the virtual reality and mixed reality conditions. From left to right: Take a Beat Portal, Firefly Treehouse, and Boxy Treehouse.

The second activity, "Firefly Treehouse," is a breathing exercise accompanied by arm movements (Figure 5). This activity takes place in a virtual setting where participants are guided to take deep breaths, raising their arms while inhaling and lowering them during exhaling. The guided audio included directions, such as "Take in a deep breath, and as you inhale raise your hands up above your head [...] Hang there for a moment and as you exhale, bring your hands back to your side." This entire activity lasts approximately 3 minutes.

The third activity, "Boxy Treehouse," is a box breathing exercise similar to the first activity, with the only difference being that it is carried out in a VR setting (Figure 5). In this box breathing exercise, participants would similarly undergo 3 sets of 4 breathing exercises. The guided audio also included similar instructions as the first activity, such as "Inhaling…feeling your chest and stomach expanding [...] Holding…feeling the breath in your body [...] Exhale… feeling the release of any tension [...] Holding… before the next breath." Throughout all 3 activities, participants were instructed to direct their attention to the present moment, feeling their breath, and being aware of each of their breaths. This entire activity lasts approximately 5 minutes.

Mind-Wandering Control

In the mind-wandering condition, participants listened to a 15-minute audio track that allowed for free mind-wandering. Participants listened to the audio using headphones on the desktop. It included instructions, such as "Now we're going to do an exercise for 15 minutes [...] Now simply think about whatever comes to mind, let your mind wander freely without thinking about anything in particular [...] Let your mind roam as it normally would [...] Allow your thoughts to wander wherever they may go [...] Go ahead and follow whatever thoughts that come to mind [...] Continue letting your mind wander, allowing your thoughts to wander wherever they may go." Throughout the mind-wandering audio, there were no mindfulness instructions or interventions given.

Procedures

The within-subject experiment (VR+MR mindfulness breathing vs mind-wandering) consisted of 2 sessions held 1 week apart in the laboratory. Data collection spanned 13 weeks during the semester, and analysis commenced only after the final session was completed. Participants were randomly assigned to either the VR and MR mindfulness breathing experimental condition or the mind-wandering control condition during their first session and assigned to the other condition in the second session, a week later. Throughout the study, the experimenter monitored participants to maintain data quality.

At the start of each session, participants received a link to the Qualtrics survey and were directed to the informed consent page. Participants used a desktop computer with headphones and a VR headset to complete the study. After providing informed consent, each participant generated a unique personal ID to be used across both sessions. Participants began each session by completing baseline measures, including the Circumplex Model of Affect, SMS-5, and OSpan. Following the baseline assessments, participants proceeded to complete activities in their assigned conditions.

After undergoing their respective conditions, a manipulation check was conducted to assess whether the participants were absorbed during the VR and MR mindfulness breathing intervention [42,98,99]. Participants rated the extent to which they felt absorbed in the present moment, focused on their breathing, and the physical sensations of their breathing. The 3 questions were asked using a 7-point Likert scale (1=*Not at all absorbed*, 7=*Extremely absorbed*), where higher scores correspond to greater levels of absorption. A manipulation check consisting of the same questions was conducted for the mind-wandering condition. Finally, they completed posttreatment measures, including the Circumplex Model of Affect, SMS-5, and RotSpan. Participants filled in their demographics at the end of the first session. At the end of the second session, participants were debriefed about the purpose of the study (Figure 6).

Figure 6. Flowchart of the study procedure illustrating the counterbalanced within-subjects design comparing brief virtual reality and mixed reality mindfulness breathing and a mind-wandering control condition. Total sample size was n=102. MR: mixed reality; VR: virtual reality.

Results

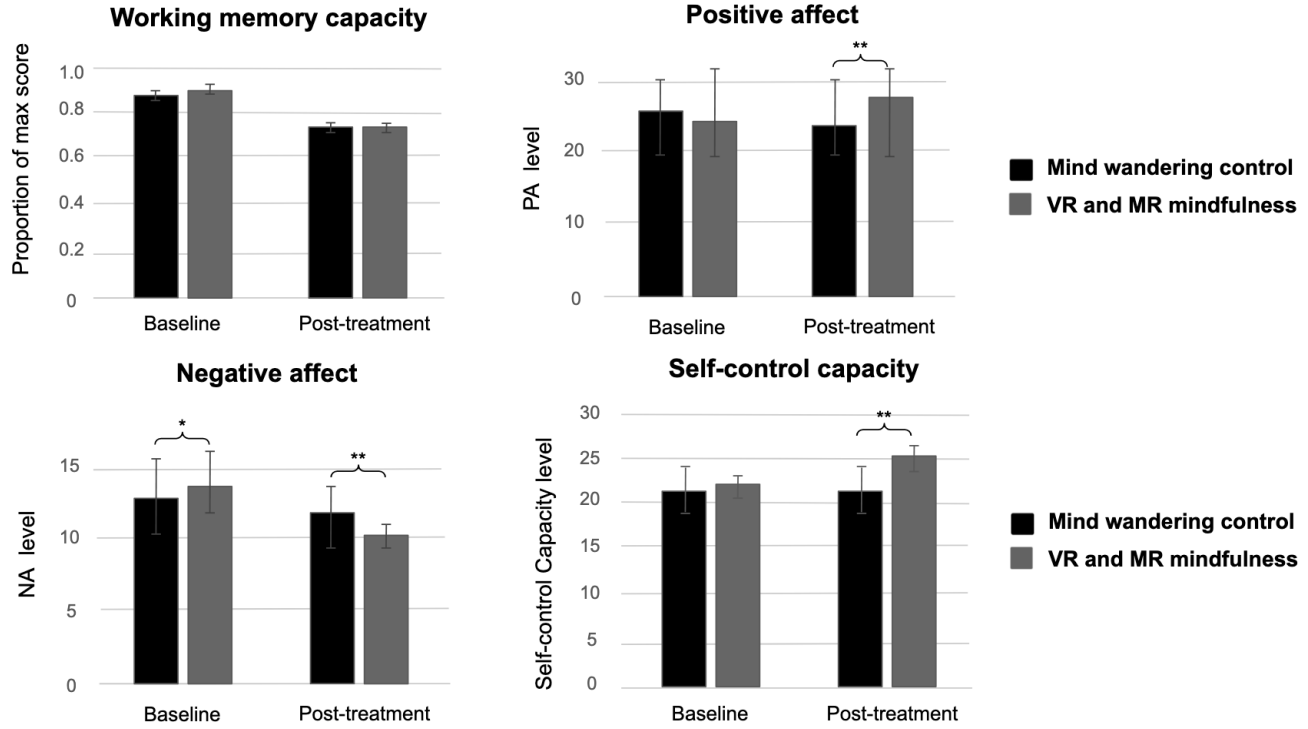
Manipulation Check

In line with our preregistration, we conducted a paired *t* test analysis, which revealed a significant difference in absorption between conditions, t_{101}=−16.29, Cohen *d*=−1.61, 95% CI −1.91 to −1.32; *P*<.001, indicating that participants reported greater absorption in the VR and MR mindfulness breathing condition (mean 15.46, SD 3.32) than in the mind-wandering control condition (mean 9.11, SD 4.07). Bayesian analysis provided extreme evidence in favor of the alternative hypothesis, BF_{10}>100 [100], indicating a substantial difference in absorption levels between conditions.

Working Memory Capacity

Following our preregistered analytic plan, differences in working memory scores between conditions via a 2 (condition: VR+MR mindfulness vs mind-wandering)×2 (time: baseline vs posttreatment) were tested using repeated-measures ANOVA. A significant main effect of time on working memory was observed ($F_{1,101}$=149.34, η_p^2=0.597; *P*<.001). However, there was no significant main effect of condition ($F_{1,101}$=0.343, η_p^2=0.003; *P*=.56). Similarly, the interaction effect between condition and time on working memory capacity was not significant ($F_{1,101}$=1.366, η_p^2=0.013; *P*=.25), and working memory scores differed similarly between baseline (mean 0.90, SD 0.13) and post treatment (mean 0.74, SD 0.18) in the VR and MR mindfulness breathing condition, and between baseline (mean 0.88, SD 0.15) and post treatment (mean 0.74, SD 0.17) in the mind-wandering control condition (Figure 7). This indicates that the difference in working memory performance between baseline and post treatment did not differ between the VR and MR mindfulness breathing condition and the mind-wandering control condition. Bayesian analysis further provided moderate evidence in support of the null hypothesis for both the main effect of condition and the time×condition interaction (BF_{01}=7.42 and BF_{01}=5.55, respectively), suggesting that VR and MR mindfulness breathing did not produce measurable improvements in working memory capacity compared to the control condition.

Figure 7. Working memory capacity (proportion of maximum score), positive affect, negative affect, and self-control capacity at baseline and post treatment across mind-wandering control and virtual reality and mixed reality mindfulness breathing conditions in a within-subjects experiment. Values indicate mean scores with error bars depicting SEs, which are consistent with the frequentist framework used for hypothesis testing. Total sample size was n=102. MR: mixed reality; NA: negative affect; VR: virtual reality.



PA

Consistent with our preregistered analytic plan, repeated-measures ANOVA was conducted to examine whether levels of PA were influenced by time and condition. First, no significant main effect of time on PA was observed after Bonferroni correction ($F_{1,101}$=5.367, η_p^2=0.050; *P*=.02). This indicates that PA did not change significantly across time, regardless of the condition. However, a significant main effect of the condition on PA was found, $F_{1,101}$=13.278, η_p^2=0.116; *P*<.001, indicating that the VR and MR mindfulness breathing condition showed significantly higher levels of PA (mean 26.47, SD 6.73) than the mind-wandering control condition (mean 24.20, SD 5.95). A Bonferroni correction was applied to account for multiple comparisons. With a corrected significance threshold of *P*<.0167 (ie, .05/3) for 3 comparisons, the main effect remained significant.

Most importantly, the interaction effect between condition and time on PA was significant, $F_{1,101}$=58.30, η_p^2=0.366; *P*<.001, suggesting that the changes in PA scores over time differed

significantly between the VR and MR mindfulness breathing condition and the mind-wandering control condition. Specifically, PA scores increased from baseline (mean 24.59, SD 6.74) to posttreatment (mean 28.35, SD 7.63) in the VR and MR mindfulness breathing condition, whereas scores in the mind-wandering control condition declined from baseline (mean 25.03, SD 6.24) to posttreatment (mean 23.36, SD 7.25), reflecting a statistically significant difference between conditions (Figure 7). This effect remained significant under the Bonferroni-corrected threshold (adjusted P<.0167). Bayesian analysis further provided extreme evidence supporting the alternative hypothesis (BF_{10}>1000, BF_{01}<0.001). The 95% credible intervals for the cell means indicated that PA decreased in the control condition from 25.03 (23.80-26.26) at baseline to 23.36 (21.94-24.79) post treatment, whereas it increased in the VR and MR mindfulness condition from 24.59 (23.26-25.91) to 28.35 (26.86-29.85).

NA

A similar analytical approach was used to examine changes in NA. A significant main effect of time on NA was observed, $F_{1,101}$=62.619, η_p^2=0.383; P<.001, suggesting that NA changed significantly from baseline to post treatment. While there was no main effect of the condition on NA, $F_{1,101}$=1.384, η_p^2=0.014; P=.24, the interaction effect between condition and time on NA was significant ($F_{1,101}$=39.087, η_p^2=0.279; P<.001). The results showed that the change in NA scores over time was significantly different between the VR and MR mindfulness breathing condition and the mind-wandering control condition. Specifically, NA scores declined from baseline (mean 14.15, SD 4.84) to post treatment (mean 10.58, SD 2.74) in the VR and MR mindfulness breathing condition, whereas the decline was less pronounced in the mind-wandering control condition from baseline (mean 13.15, SD 5.12) to post treatment (mean 12.36, SD 4.27). This effect remained statistically significant under the Bonferroni-corrected threshold (adjusted P<.0167). Bayesian analysis also provided extreme evidence in favor of the alternative hypothesis (BF_{10}>1000, BF_{01}<0.001). The 95% credible intervals indicated that NA decreased modestly in the control condition, from 13.15 (12.14-14.15) at baseline to 12.36 (11.52-13.20) post treatment, but showed a substantially larger decrease in the VR and MR mindfulness condition from 14.15 (13.20-15.10) to 10.58 (10.04-11.12).

Self-Control Capacity

Similar analyses were conducted to examine changes in self-control capacity. A significant main effect of time was observed, $F_{1,101}$=15.480, η_p^2=0.133; P<.001, indicating that self-control capacity changed significantly from baseline to post treatment. Moreover, a significant main effect of condition was found, $F_{1,101}$=24.910, η_p^2=0.198; P<.001, and remained statistically significant after the Bonferroni correction. Consistently, the interaction effect between condition and time on self-control capacity was also statistically significant ($F_{1,101}$=28.348, η_p^2=0.219; P<.001). The results showed that self-control capacity scores increased from baseline (mean 22.09, SD 4.60) to post treatment (mean 25.25, SD 4.42) in the VR and MR mindfulness breathing condition, whereas scores in the mind-wandering control condition decreased from baseline (mean 21.77, SD 5.14) to post treatment (mean 21.31, SD 5.46). Bayesian analysis further provided extreme evidence in favor of the alternative hypothesis (BF_{10}>1000, BF_{01}<0.001). Collectively, these findings suggest that exposure to VR and MR mindfulness breathing was associated with an improvement in self-control capacity.

Discussion

Despite the growing body of research on mindfulness, much of the existing literature focuses on intensive, multisession interventions [46,78], leaving a gap in our understanding of the effectiveness of brief mindfulness practices. Some evidence suggests that even a single session of mindfulness can produce temporary benefits, but findings remain inconsistent, highlighting the need for more engaging and immersive approaches [42,60-62]. This study examined whether immersive VR technologies could enhance the effectiveness of brief mindfulness practices, potentially offering a more engaging and effective alternative. Brief mindfulness interventions often face challenges, such as limited attentional depth, insufficient repetition to consolidate self-regulatory skills, and inconsistent environmental contexts, that hinder transfer to daily life [66]. VR and MR-based delivery may help address these limitations by providing immersive environments that minimize distraction, provide sustained attentional focus, and simulate realistic emotional situations for practicing acceptance [66-68].

Consistent with our hypothesis, both VR and MR mindfulness breathing improved emotional well-being by increasing PA and reducing NA. These findings align with previous research showing that mindfulness breathing enhances PA [7,13,14] while alleviating depressive symptoms [7,101], stress [10,20,21], and anxiety [22,23,101]. According to the monitor and acceptance theory [56], mindfulness promotes emotion regulation through two core components: (1) attention monitoring, which heightens present-moment awareness; and (2) acceptance, which enables individuals to observe emotions without reacting impulsively. The immersive nature of VR and MR may further strengthen these processes by increasing engagement, reducing external distractions, and fostering a heightened sense of presence during mindfulness practice [66,102]. By creating a more absorbing and controlled environment, VR and MR may deepen both attention monitoring and acceptance, leading to greater emotional benefits [51,69]. It is also important to note that mindfulness aims to cultivate adaptive flexibility [34], allowing individuals to experience and regulate both positive and negative emotions in a context-sensitive manner. Our findings suggest that even a brief 15-minute mindfulness breathing session can enhance emotional well-being, adding to evidence that short-duration mindfulness interventions can yield immediate psychological benefits. Overall, these findings underscore the potential of VR and MR as effective tools for mood enhancement by strengthening core mindfulness processes. However, it is also possible that part of the emotional improvements observed may partly reflect the novelty and sensory engagement of immersive VR itself rather than mindfulness-specific mechanisms. Previous research shows

that immersive VR can induce relaxation and PA through heightened presence and environmental realism, even without formal mindfulness instruction [67]. Thus, the affective benefits observed in this study may reflect a combination of novelty, attentional engagement, and mindfulness-related processes.

Beyond its benefits for emotional well-being, the study found that VR and MR mindfulness breathing also enhanced self-control capacity. Participants in the VR and MR conditions demonstrated greater self-control than those in the mind-wandering control condition, consistent with previous research showing that brief mindfulness practice can counteract self-control depletion [103,104]. This effect may stem from mindfulness enhancing 2 fundamental self-control processes: (1) emotion regulation [17-19] and (2) attention regulation [46,47,105], both of which are crucial for maintaining self-regulatory capacity [44,48]. The immersive qualities of VR and MR may further amplify these effects by deepening attentional absorption, minimizing external distractions, and alleviating cognitive strain. By reducing cognitive load, VR and MR mindfulness exercises may help preserve the mental resources necessary for self-control, thereby reinforcing self-regulatory functioning [44]. These findings contribute to the growing literature on mindfulness and self-control regulation and suggest that brief VR and MR mindfulness interventions could be useful for mitigating self-regulatory depletion [35,106]. Such interventions may be particularly suitable for individuals seeking to restore attentional and self-control resources during breaks in cognitively demanding environments, including workplaces and educational settings. By stabilizing attentional focus and alleviating cognitive strain, these interventions may enhance both productivity and well-being [52].

Contrary to our hypothesis, we found no significant difference in working memory between the VR and MR mindfulness and mind-wandering control conditions. This contrasts with previous research showing that mindfulness training can enhance working memory [32,33], suggesting potential limits to the immediate cognitive benefits of brief interventions in immersive VR and MR formats. These results highlight the need for caution when interpreting short-term cognitive outcomes following minimal exposure and are consistent with evidence that improvements in working memory typically emerge only after prolonged, repeated mindfulness training over multiple sessions [62,92]. Future research should therefore investigate whether extended VR and MR mindfulness programs yield cumulative cognitive gains as participants become more familiar and engaged with the practice.

Several factors may help to explain the limited cognitive benefits observed in our study. First, intervention duration and intensity are critical. Previous research indicates that mindfulness-based interventions typically require multisession practice to yield measurable cognitive benefits [33,42]. For example, studies in which participants engaged in 30 - 45 minutes of mindfulness training over several weeks have reported measurable improvements in working memory [33,42]. In contrast, the single 15-minute session in our study may not have provided sufficient opportunity for participants to fully engage with the mindfulness practice or experience cognitive benefits. Moreover, working memory capacity is relatively stable and tends to change gradually rather than in response to brief interventions [107,108]. Given that working memory relies on complex neural processes that require continuous reinforcement [109,110], longer training durations may be necessary to induce measurable improvements. This account aligns with evidence that the cognitive benefits of mindfulness depend on repeated and prolonged engagement, which strengthens underlying attentional and working memory mechanisms [4,32,54,55]. Future research should therefore explore whether extended VR and MR mindfulness interventions produce cumulative cognitive gains over time. It will be important to determine whether repeated practice enhances working memory or whether habituation results in reduced engagement. Clarifying these long-term dynamics is crucial for evaluating the feasibility of VR and MR-based mindfulness as a long-term cognitive intervention.

An alternative explanation for the lower working memory scores observed post treatment relative to baseline is the influence of uncontrolled stressors or fatigue during the study period. Academic workload, sleep disruption, or daily emotional stress may have temporarily impaired prefrontal functioning and reduced attentional capacity during testing [111-113]. Previous research indicates that acute stress can disrupt working memory by diverting cognitive resources from executive processes [114]. Repeated testing may also have contributed to cognitive fatigue, particularly given the demanding nature of the complex span tasks [109]. The comparable pattern observed across both conditions suggests that these differences reflect general influences rather than effects of the experimental manipulation itself.

Beyond intervention duration and intensity, the environmental context of mindfulness practice may also influence cognitive outcomes. While previous studies have often used nature-based settings (eg, forests, rivers, and beaches) for mindful practice, which have been known to promote relaxation and reduce cognitive load [66,115], our study used VR metaverse and MR environments. Although VR and MR provide immersive experiences, they may also introduce additional cognitive demands, such as the need to navigate virtual interfaces, which could detract from mindfulness engagement, particularly for individuals unfamiliar with the technology [82]. This may help explain why VR and MR did not yield measurable cognitive improvements; compared with natural environments, immersive virtual settings may not provide the restorative conditions necessary for cognitive recovery [92], potentially contributing to the null findings in our study.

While this study highlights the potential psychological benefits of VR and MR mindfulness interventions, several limitations should be considered. First, future research should include more diverse samples to enhance generalizability beyond young adults. Younger participants may differ from older adults or clinical populations in their adaptability to emerging technology and stress profiles [78]. Including individuals from a wider range of age groups, occupational backgrounds, and mental health conditions would provide a more comprehensive understanding of the effectiveness of VR and MR mindfulness interventions.

Second, the working memory assessment in this study may be subject to task impurity [116,117]. We used the OSpan task at baseline and the RotSpan task post treatment, which engage different cognitive processes (eg, verbal vs spatial processing) [83]. Relying on only 2 complex-span tasks may have provided an incomplete evaluation of working memory capacity, making the null findings potentially task-specific rather than reflective of actual cognitive changes. In addition, we did not include tasks from other paradigms, such as N-back or updating tasks, which assess complementary components of working memory (eg, tracking, updating, and replacing information) [108]. Future research should incorporate a broader set of complex span tasks to improve construct validity.

Third, the study did not account for individual differences in stress exposure, fatigue, or sleep quality across sessions. Variability in these uncontrolled factors may have contributed to fluctuations in working memory performance, underscoring the need for future studies to monitor or standardize participants' stress levels across testing periods [118]. Another limitation concerns participants' familiarity with VR technology. Because our sample primarily consisted of young adults, their higher levels of technological comfort may have facilitated immersion and engagement during the intervention. These effects may not generalize to older adults or clinical populations with limited VR experience. Future research should therefore assess VR familiarity as a potential moderator and examine whether individual differences in technological comfort influence intervention outcomes.

Finally, the absence of a VR-based control condition (ie, a nonmindfulness VR control condition) presents another limitation. We selected a mind-wandering task as the control condition to ensure that participants engaged in a cognitively active but nonmindful activity, thereby providing a clearer contrast with the mindfulness intervention [43]. Although this design differentiates mindfulness-specific effects from general cognitive engagement, it does not fully disentangle the potential contribution of VR immersion itself from those of mindfulness practice. Future research should include an appropriate VR control condition to clarify the distinct contributions of immersion and mindfulness.

In summary, this study examined the effects of VR and MR mindfulness on cognitive and emotional outcomes relative to a mind-wandering control condition. While no cognitive improvements were observed, the findings underscore the potential of VR and MR mindfulness in enhancing emotional well-being, consistent with research suggesting that immersive environments may facilitate psychological benefits [71,79]. In comparison to existing studies that have primarily focused on stress reduction or relied on multisession digital interventions [46,78], this study demonstrates that a single brief VR or MR session can enhance key emotional and self-regulatory outcomes. As such, these findings underscore the potential of VR and MR mindfulness applications as innovative and scalable tools for promoting mental well-being. As these technologies become increasingly incorporated into mental health interventions, future research should investigate their long-term efficacy and applicability across diverse populations and identify the specific features, such as sensory immersion, attentional focus, and guided engagement, that optimize their therapeutic potential. Furthermore, the declining cost and increasing accessibility of stand-alone VR headsets (eg, Meta Quest) increase the feasibility of implementing immersive mindfulness programs in organizational and educational settings [68]. Despite initial setup and training demands, these interventions can be cost-effective over time because the same digital content can be reused across participants with minimal supervision. Their scalability and portability make them suitable for brief restorative sessions that enhance attention and emotional well-being [92]. Future research should therefore examine implementation feasibility, including usability, cost-benefit considerations, and long-term adherence, to determine the broader applicability of VR- and MR-based mindfulness interventions. By leveraging the unique affordances of immersive technology, VR and MR mindfulness may provide innovative and accessible approaches to enhancing emotional regulation and well-being across clinical, educational, and workplace settings.

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A Generative Artificial Intelligence tool (i.e., ChatGPT) was used only for refinement, correction, editing, or formatting of the manuscript to improve clarity of language.

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Data Availability

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

Authors' Contributions

ZKYE: Methodology, Writing – original draft, Writing – review & editing.
CKJ: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.
HY: Writing – original draft, Writing – review & editing.

AYHG: Conceptualization, Methodology.
MH: Conceptualization, Methodology.
KTASK: Conceptualization, Methodology.
AH: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Conflicts of Interest

None declared.

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Abbreviations

JARS: Journal Article Reporting Standards
MBSR: mindfulness-based stress reduction
MR: mixed reality
NA: negative affect
OSpan: operation span
PA: positive affect
RotSpan: rotation span
VR: virtual reality

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Mixed Reality–Based Slit Lamp for Ophthalmic Examination and Telemedicine: Technological Development and Validation Study

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Abstract

Background: The slit-lamp biomicroscope is a fundamental diagnostic tool in ophthalmology for detailed examination of the eye. Current camera-equipped digital slit lamps were designed with a single optical channel, which results in the loss of depth information. Without that information, it can be challenging to visualize subtle anatomical variations in teleophthalmology applications and perform procedures guided by the digital view.

Objective: This study aimed to present a feasibility study of the mixed reality (MR)–based slit lamp (MR-SLP) capable of transmitting real-time stereoscopic views of the slit lamp to local and remote MR headsets, enabling stereoscopic teleophthalmology.

Methods: A prototype MR-SLP was built by integrating a calibrated stereoscopic camera pair on the left and right viewing channels of a conventional slit lamp and a real-time streaming network. The stereoscopic diagnostic images were transmitted to multiple MR headsets through the streaming network at 1080p and 30 frames per second (fps). The spatial resolution of the system was quantified using a US Air Force 1951 resolution target (Edmund Optics Inc). The 3D spatial accuracy and coordination were evaluated quantitatively by performing a tube-threading test. Five participants (mean age 42.2, SD 16.5 years) with normal visual function, best-corrected visual acuity of 20/20 or better, and a minimum stereoacuity of approximately 40 arc seconds participated in the tube-threading test. Teleophthalmology capability was assessed through real-time streaming across multiple remote sites at Florida International University and Bascom Palmer Eye Institute.

Results: The measured spatial resolution reached 102 line pairs/mm at 25× optical magnification. The tube-threading task was performed under 4 conditions. Task performance differed significantly between nonstereoscopic (2D) and direct eyepiece views (P=.03, Kruskal-Wallis test), but not between stereoscopic (3D) MR and direct views (P>.05, Kruskal-Wallis test). In the real-time remote streaming tests across multiple sites, the system achieved stable, low-latency transmission with an average round-trip time below 40 milliseconds. Participating ophthalmologists reported user experience and image quality comparable to traditional slit lamps.

Conclusions: The MR-SLP can provide real-time stereoscopic slit-lamp examination images and videos through a broadcasting network to local and remote locations. The spatial resolution and visuomotor performance are comparable to direct viewing through the eyepieces of a traditional slit lamp. This study demonstrated the feasibility of the MR-SLP for high-quality stereoscopic teleophthalmology.

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KEYWORDS

telemedicine; teleophthalmology; mixed reality; slit-lamp microscopy; depth perception; wearable; remote consultation

Introduction

The slit-lamp biomicroscope is a fundamental diagnostic tool in ophthalmology for detailed examination of both the anterior and posterior segments of the eye [1] with stereoscopic visualization [2]. Traditional slit lamps require the operator to view through the eyepieces to obtain a stereoscopic perspective. This necessity means the operator must stay close to the patient, which has become more concerning since the COVID-19 pandemic, given that close contact increases the risk of transmitting infectious diseases [3,4]. Modern slit lamps frequently come with a camera, whether dedicated or integrated into a smartphone, allowing them to capture images and videos of the eye during examinations. This feature is especially beneficial for data collection, telemedicine, and education, as captured images and videos can be viewed on a display, stored electronically, and shared remotely [5-7]. Current camera-equipped slit lamps often use a single-channel design, resulting in the loss of stereoscopic information and,

consequently, depth perception during image and video capture. Without depth perception, it can be challenging to visualize subtle anatomical variations and perform procedures guided by the slit-lamp view [8].

Mixed reality (MR) technology enables interactive experiences that blend both real and virtual environments by using a head-mounted display (HMD). A HMD is a wearable device designed to fit comfortably over the user's head, equipped with a stereo camera and individual screens for each eye. Additional sensors are incorporated to accurately track head and eye movements. The MR headset's see-through function allows users to view the real world with depth perception. By seamlessly blending digital content with the real world, MR facilitates intuitive interaction and manipulation of virtual objects within the user's actual environment. These advancements make MR a promising tool for applications such as 3D medical data visualization and telemedicine [9,10].

To address the limitations of conventional slit-lamp examinations in remote collaboration and stereoscopic information sharing, we developed the MR-based slit lamp (MR-SLP) that integrates MR technology with a traditional slit lamp. The MR-SLP enables local operators to interact naturally with patients using its see-through function while simultaneously visualizing a stereoscopic diagnostic view; it also allows real-time streaming of the view to remote physicians wearing headsets for immersive participation. This functionality supports collaborative decision-making, as remote specialists can actively guide local operators during examinations, and enables recording of stereoscopic diagnostic images and videos for documentation and education. In this study, we aim to develop and evaluate the MR-SLP system and assess its capability for real-time stereoscopic imaging, remote visualization, and collaborative ophthalmic examination and telemedicine.

Methods

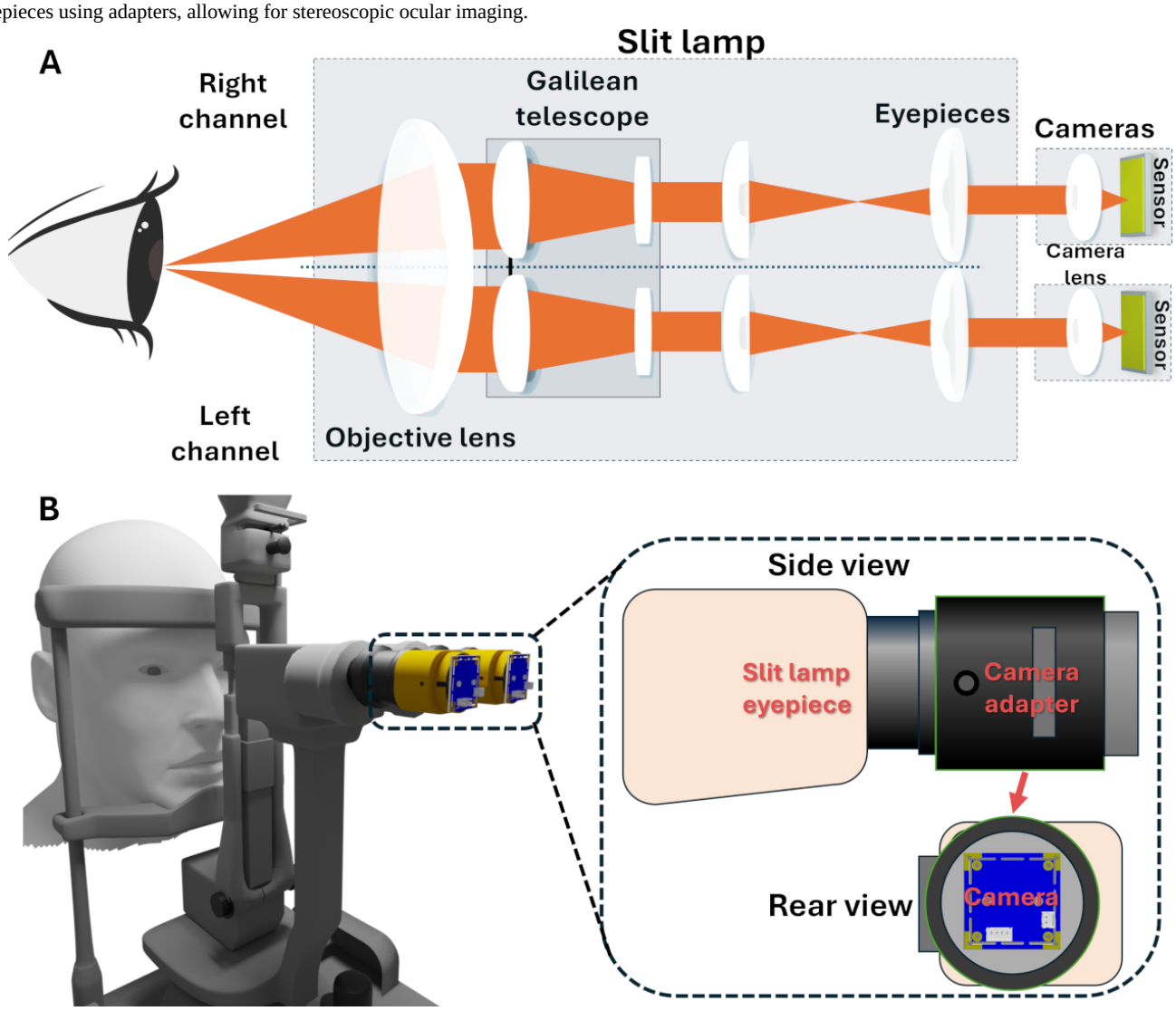
Ethical Considerations

The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the institutional review board (IRB) of Florida International University (IRB-19 - 0112-CR02 and IRB-26 - 0004). Written informed consent was obtained from all participants prior to enrollment. All data were deidentified before analysis, and no personally identifiable information or protected health information was collected or stored by the MR-SLP system.

System Design

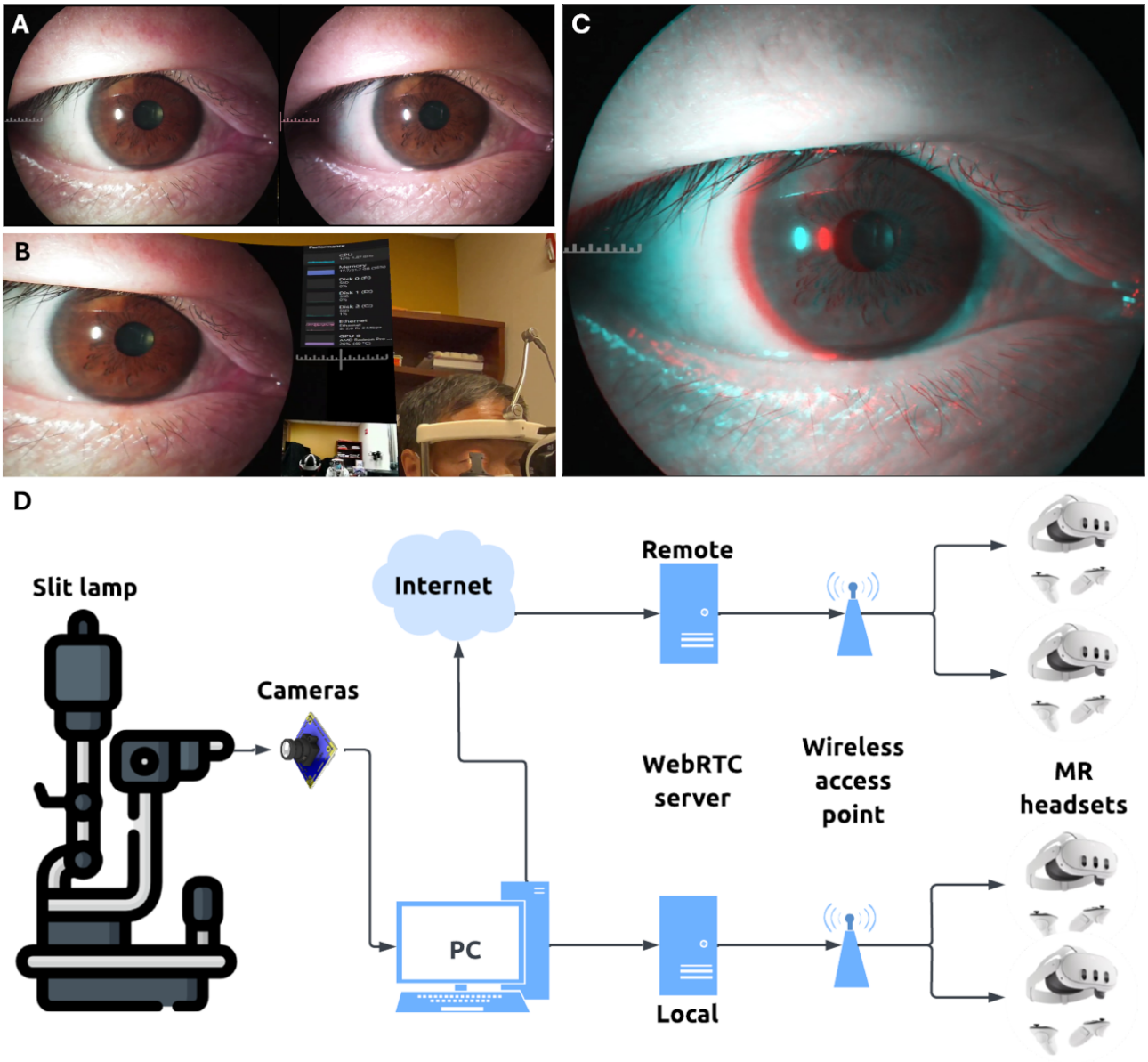
The MR-SLP system developed in this study was built on a commercial slit lamp (XCEL250, Recheit Inc). Two board-level USB video cameras (ELP-USB16MP01-L75, 1/2.8-inch sensor, maximum resolution: 4656×3496 pixels) formed a stereoscopic pair and were calibrated before mounted on the left and right eyepieces using custom-designed adapters. The adapters allow fine-tuning of the cameras' positions to ensure accurate alignment of their optical axes with the eyepieces. A schematic of the system is shown in Figure 1.

Figure 1. Design of the mixed reality–based slit-lamp (MR-SLP) system. (A) Schematic of the optical path of the MR-SLP. Light reflected by the examined area enters the front objective lens, then proceeds through the Galilean telescope assembly and the eyepieces before reaching the camera lens and being detected by imaging sensors. (B) Adaptation of a traditional slit lamp for MR-SLP functionality. Two cameras are mounted on the slit-lamp eyepieces using adapters, allowing for stereoscopic ocular imaging.



The videos captured by the 2 cameras were first streamed via USB to a local computer, where they were processed in real time using Open Broadcaster Software Studio (64-bit, version 31.0), an open-source video streaming application. For the video processing pipeline in Open Broadcaster Software Studio, we used the NVIDIA NVENC H.264 hardware encoder to achieve efficient, low-latency streaming. The encoder settings were specifically tuned for real-time performance. Key parameters included rate control set to constant bitrate, bitrate at 10 Mbps, keyframe interval set to 0 seconds for automatic management, and preset configured to “fastest” with “ultra low latency” tuning. The stream used the “baseline” profile to maximize compatibility and minimize processing overhead. The processed videos were formatted into side-by-side 3D mode (Figure 2A), a widely used format for conveying stereoscopic information in image processing [11]. Subsequently, the side-by-side 3D video was transmitted to local and remote Web Real-Time Communication (WebRTC) servers using the WebRTC HTTP ingestion protocol, with an output resolution of either 1080p or 720p. For local streaming, a free WebRTC server (OSSRS/SRS v6.0 from Docker Hub) was deployed on a PC, while remote streaming was facilitated by a commercial WebRTC service provided by dolby.io over the internet. The processed streams were broadcasted wirelessly to MR headsets using the WebRTC HTTP egress protocol. The headsets (Meta Quest 3; Meta Platforms Inc) then rendered the stream into a stereoscopic view with their built-in video player for immersive visualization (Figure 2B). An image in red-cyan stereoscopic format is provided (Figure 2C) as an example, which can be viewed using red-cyan anaglyph 3D glasses. A diagram of the broadcasting architecture is shown in Figure 2D.

Figure 2. Imaging procedures from camera to the head-mounted display (HMD)–rendered display. (A) Example images of a participant's eye captured with the mixed reality (MR)–based slit-lamp (MR-SLP) cameras in the side-by-side 3D (SBS) format. (B) The view of the local operator through their MR headset. The embedded window on the left displays the stereoscopic view (rendered from the SBS video) of the participant's eye. The participant and the environment are seen with the see-through function of the MR headset. (C) An image in red-cyan stereoscopic format demonstrates the 3D view as an example that can be observed using red-cyan anaglyph 3D glasses. (D) Broadcasting system architecture. The videos captured by the cameras on a slit lamp are processed by a local PC and transmitted wirelessly to local and remote MR headsets via Web Real-Time Communication (WebRTC) servers.



Spatial Resolution Evaluation

A US Air Force 1951 resolution target (Edmund Optics Inc) was used to evaluate the spatial resolution of the MR-SLP. The target was placed at the imaging plane of the MR-SLP and imaged at 25× optical magnification. Raw images of the resolution target were captured using the MR-SLP's USB cameras with the built-in camera app on Microsoft Windows 11, at a resolution of 4656 × 3496 pixels, which is the cameras' maximum resolution. Images displayed in the MR headset were captured through real-time video streaming, using the built-in snapshot tool of the Meta Quest 3 at a resolution of 1080p.

Intensity profiles were generated across the line pairs for selected group–element combinations from the acquired resolution target images using MATLAB (MathWorks Inc). The minimum resolvable line pairs were determined according to the Rayleigh criterion, wherein the central maximum of one pattern coincides with the first minimum of another. Additionally, a subjective evaluation was conducted in which participants compared the minimum readable line pairs observed directly through the eyepieces with those visible in the images captured via camera.

Tube-Threading Test for Evaluating Visuomotor Performance With the MR-SLP

To assess the visuomotor performance of the MR-SLP, a tube-threading test was designed based on the concept of a bead-threading task [12,13], a well-known method for estimating fine visuomotor performance that was critically affected by depth perception. This tube-threading test consisted of 2

sequential tasks. In task 1, the participant was asked to pick up each of the 10 tubes from a container using a tweezer, place the tube at the focal plane of the slit lamp to be seen clearly, and then return the tube to the container. In task 2, the participant was asked to pick up each tube, thread a wire into it under the visual guidance of the slit lamp, and return the tube to the container. The participants were required to complete 2 tasks 5 times under each designed condition shown in Table 1. High-precision tweezers (PL-30; Fisher Scientific) primarily for microscopy applications were used to grab the tubes. The tubes used in this test were made from micropipette tips. Their outer diameter ranged from 0.8 mm to 1.6 mm, and their inner diameter ranged from 0.4 mm to 1.2 mm. The diameter of the wire used in this test was 0.2 mm. The small size of these tubes and the wire, combined with 10× optical magnification of the slit lamp, required precise depth perception to complete the designed tasks.

Five individuals aged between 21 and 61 years (mean 42.2, SD 16.5 years) were recruited for this test. All participants provided written informed consent to participate in the study. Each participant had normal visual function, with a best-corrected visual acuity of 20/20 or better and a minimum stereoacuity of approximately 40 arc seconds, assessed using random-dot stereograms [14]. All participants did not have any history of ophthalmologic surgery, ocular motility disorders, known fine motor impairments, or other physical impairments that could interfere with the task performance. All participants completed a short acclimation session before the main test. This included (1) adjusting the eyepieces and MR headset to achieve a full field of view at test magnification, (2) finding a comfortable position so that their body and hands were stable and at ease while performing the tube-threading test, and (3) practicing the tube-threading task until they felt comfortable.

Table . Test conditions used in the tube-threading evaluation.

Condition ID (c)	Conditions	Description
1	MR-SLP[a], 2D, 60 fps[b]	Nonstereoscopic stream[c], output resolution 720p, frame rate 60 fps, with MR[d] headset.
2	MR-SLP, 3D, 30 fps	Stereoscopic stream, output resolution 720p, frame rate 30 fps, with MR headset.
3	MR-SLP, 3D, 60 fps	Stereoscopic stream, output resolution 720p, frame rate 60 fps, with MR headset.
4	Conventional slit lamp	Direct view through the eyepieces of the slit lamp, without MR headset.

[a]MR-SLP: mixed reality–based slit lamp.

[b]fps: frames per second.

[c]Nonstereoscopic stream was created by converting the video from a single mixed reality–based slit-lamp camera into the side-by-side 3D format.

[d]MR: mixed reality.

The time taken for each task under each condition was individually recorded, denoted as Ttask1(p,c,i) and Ttask2(p,c,i), where *p* is the participant number, *c* is the condition ID, and *i* is the repeat.

From a single repeat, the time to thread the tube Tthr(p,c,i)was calculated as

$$(1) Tthr(p,c,i)=Ttask2(p,c,i)-Ttask1(p,c,i)$$

The mean of Ttask1(p,c,i) and Tthr(p,c,i) from the 5 repeats of a given participant under the same condition were calculated as

$$(2) T\text{-}task1(p,c)=15\sum i=15Ttask1(p,c,i), T\text{-}thr(p,c)=15\sum i=15Tthr(p,c,i)$$

and Ttask2(p,c,i) taken for each task under each condition was individually recorded. T-task1(p,c) and T-thr(p,c) for all 4 conditions were collectively analyzed using statistical methods to identify the effects of the test conditions on participants' performance.

Telemedicine Assessment

A telemedicine assessment was conducted to evaluate the streaming quality, remote usability, and applications of the MR-SLP. Five participants were assigned to different roles across 3 locations in Miami. The local site was at the main campus of Florida International University, where an ophthalmologist with around 10 years of clinical experience operated the MR-SLP and performed test examinations on a volunteer with normal visual function. Stereoscopic slit lamp video was captured and streamed in real time at an output resolution of 1080p. Simultaneously, a second ophthalmologist with more than 20 years of clinical experience watched the stereoscopic video from the MR-SLP using an MR headset at the first remote site, Bascom Palmer Eye Institute at the University of Miami Miller School of Medicine. He communicated in real-time with the MR-SLP operator at the local site, providing expert guidance and diagnostic opinions. In addition, a senior scientist at the first remote site also observed the examination procedure through an MR headset for technical assistance. Finally, a senior scientist at the second remote site, the Florida International University Engineering Center, observed the process using an MR headset. All local and remote participants verbally assessed the system's technical performance, including image quality and streaming stability. The latency, particularly the round-trip time, was provided by the remote WebRTC platform. Real-time audio communication between the local operator and remote participants was enabled using Zoom (Zoom Communications, Inc).

Data Analysis

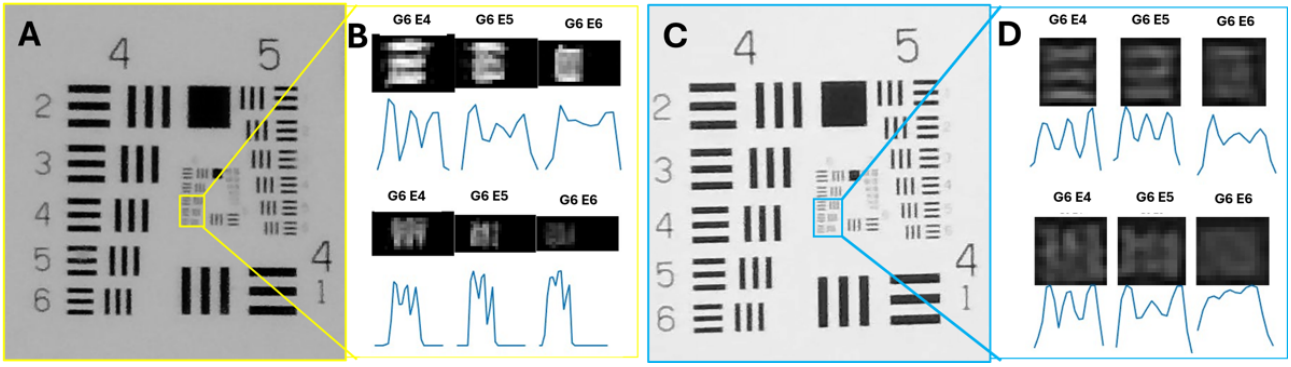
Statistical analyses were performed using R (version 4.5.1; R Foundation for Statistical Computing). The normality of the tube-threading task completion times was assessed using the Shapiro-Wilk test. Given the nonnormal distribution of the data, the nonparametric Kruskal-Wallis test was used to compare conditions, followed by post hoc analysis using the Dunn test with Bonferroni correction. Statistical significance was set at $P<.05$.

Results

Image Quality of the MR-SLP: Spatial Resolution

Our objective analysis revealed that both the MR-SLP cameras and MR headset were able to resolve element 5 in group 6 of the resolution target, corresponding to a spatial resolution of 102 line pairs/mm with a line width of approximately 9.8 µm (Figure 3). Additionally, we conducted a subjective evaluation with 3 participants who had a best-corrected visual acuity of 20/20 or better. These participants noted that, although they could discern element 5 in group 6 through the MR headset, they were able to identify up to element 6 in group 6 (114 line pairs/mm) when viewing directly through the slit-lamp eyepieces. All participants noted that the lines appeared slightly clearer when viewed through the traditional slit lamp compared with the MR headset display. This subjective difference may indicate that the fidelity of the current digital imaging pathway, which includes the camera and display, may not match that of direct optical viewing with the human eye.

Figure 3. Resolution target imaging. (A) Image of the line pairs (lps) from groups 4 to 6 for the resolution target captured directly by the mixed reality (MR)–based slit-lamp camera. (B) The upper panel shows the intensity profiles across the horizontal lps of elements 4 to 6 in group 6; the bottom panel displays the intensity profiles across the vertical lps. (C) Image of the lps from groups 4 to 6 of the resolution target captured from the MR headset. (D) The upper panel shows the intensity profiles across the horizontal lps of elements 4 to 6 in group 6; the bottom panel shows the intensity profiles across the vertical lps.



Tube-Threading Test With the MR-SLP

All participants successfully completed 2 sequential tasks (Figure 4) within a reasonable timeframe (<10 min). Their T-task1(p,c) and T-thr(p,c) records are summarized in Tables 2 and 3, respectively. According to the records, T-task1(p,c) was typically the shortest in the direct view condition (c=4). A Shapiro-Wilk test was conducted with T-task1(p,c) and T-thr(p,c) for each test condition. The test outcome indicated that the assumption of a normal distribution was not applicable in this dataset. Therefore, a nonparametric method, the Kruskal-Wallis test, was used to compare T-task1(p,c) and T-thr(p,c) under different conditions. Please find the whole dataset in Table S1 and Table S2 in Multimedia Appendix 1.

Figure 4. The tube-threading test and results. (A) The participant uses tweezers to grasp a tube, (B) positions the tube into the slit lamp's field of view until it is clearly visible, and (C) threads a wire into the tube under the slit lamp's view. (D) Box plot of Ttask1(p,c,i) across the 4 test conditions. (E) Box plot of Tthr(p,c,i) across the 4 test conditions. Each dark dot represents an individual time record, and the red diamond symbol represents the mean value. *P<.05 between 2 conditions; fps: frames per second. MR: mixed reality; ns: no statistically significant difference.

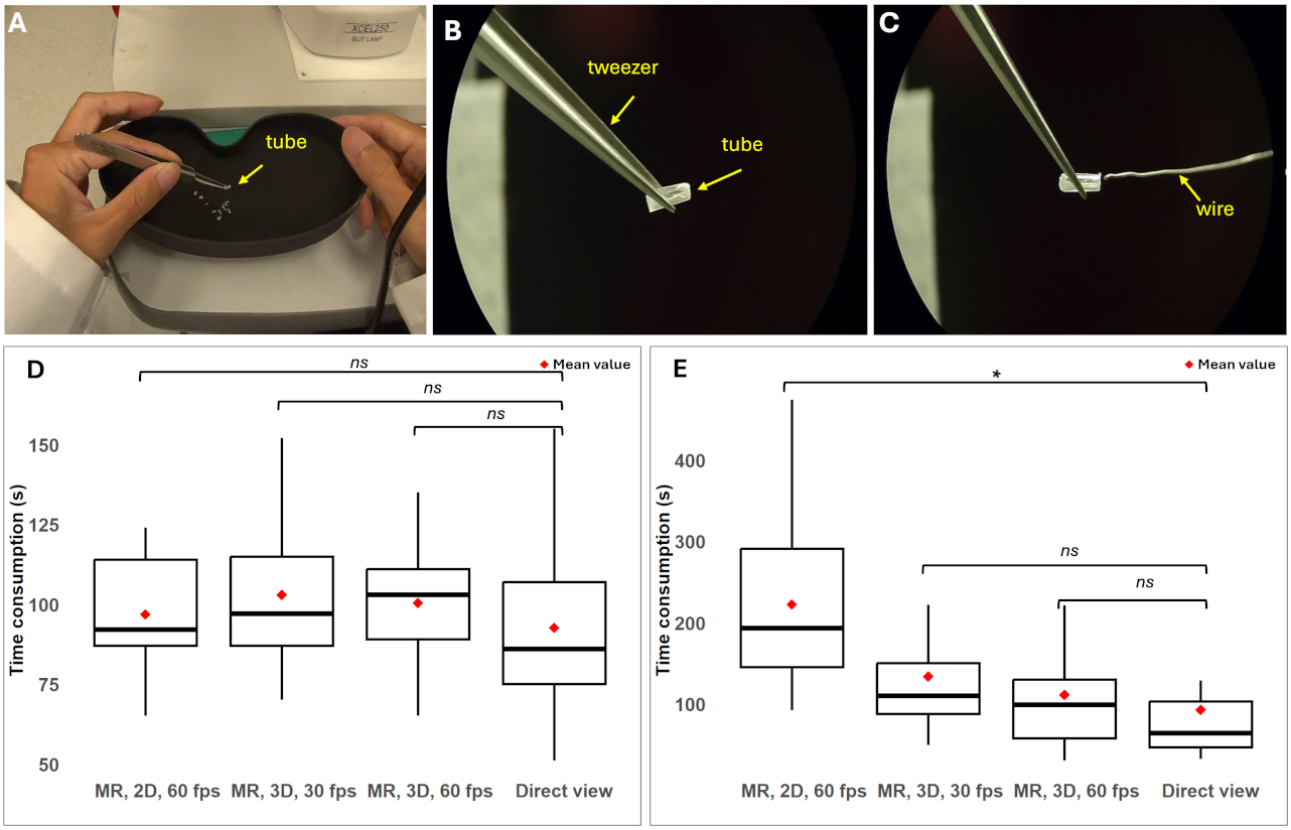


Table . T-task1(p,c) of all participants under all 4 test conditions.[a]

Participant (p)	MR[b], 2D, 60 fps[c,d], mean (SD)	MR, 3D, 30 fps[e], mean (SD)	MR, 3D, 60 fps[f], mean (SD)	Direct view[g], mean (SD)
1	77 (9)	92 (7)	84 (18)	63 (9)
2	107 (12)	126 (15)	111 (7)	116 (29)
3	118 (4)	120 (8)	124 (22)	107 (9)
4	91 (5)	93 (8)	91 (2)	75 (5)
5	91 (11)	85 (17)	91 (19)	103 (31)

[a]Time was recorded in seconds, and each number represents the mean (SD) from the 5 repeats.

[b]MR: mixed reality.

[c]fps: frames per second.

[d]Condition ID 1.

[e]Condition ID 2.

[f]Condition ID 3.

[g]Condition ID 4.

Table . T-thr(p,c) of all participants under all 4 test conditions.[a]

Participant (p)	MR[b], 2D, 60 fps[c,d], mean (SD)	MR, 3D, 30 fps[e], mean (SD)	MR, 3D, 60 fps[f], mean (SD)	Direct view[g], mean (SD)
1	241 (100)	138 (77)	153 (124)	68 (29)
2	317 (119)	133 (39)	110 (20)	76 (38)
3	131 (26)	92 (14)	75 (30)	57 (18)
4	175 (56)	93 (37)	69 (25)	48 (10)
5	249 (113)	213 (120)	149 (81)	215 (139)

[a]Time was recorded in seconds, and each number represents the mean (SD) from the 5 repeats.

[b]MR: mixed reality.

[c]fps: frames per second.

[d]Condition ID 1.

[e]Condition ID 2.

[f]Condition ID 3.

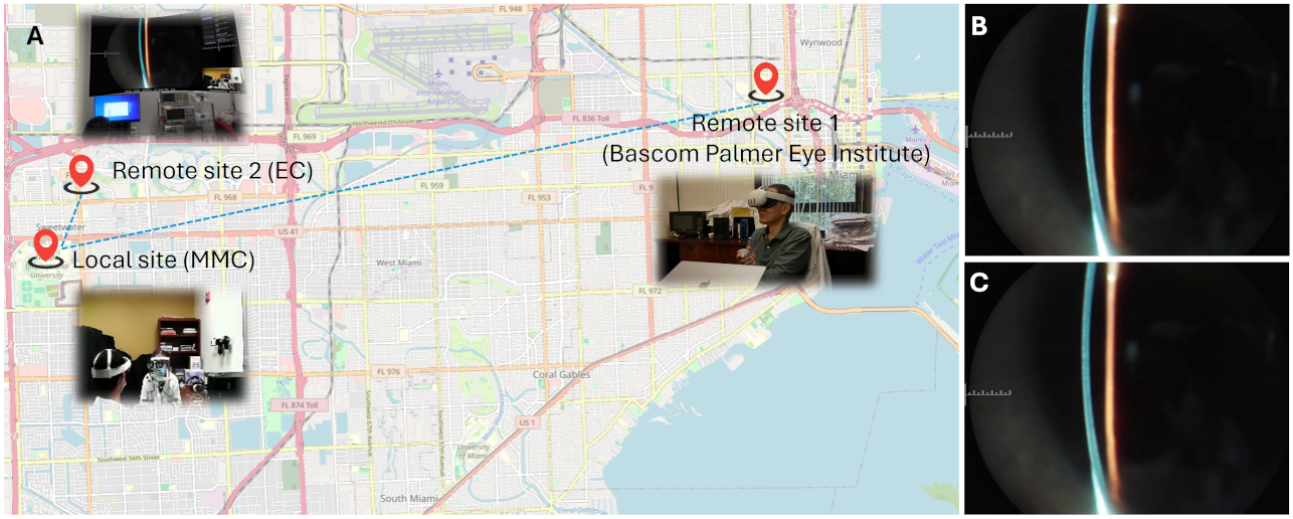
[g]Condition ID 4.

As shown in Figure 4D, the distribution of Ttask1(p,c,i) for all 4 test conditions are similar. This observation was confirmed by the result of the Kruskal-Wallis test, indicating that there were no significant differences among T-task1(p,c) for all 4 conditions (n=20; *P*=.77). According to the trend depicted in Figure 4E, the mean value of T-thr(p,c) for each condition was the shortest in the direct view condition (c=4) and gradually increased from test condition 3 (MR 3D 60 frames per second [fps]) to test condition 2 (MR 3D 30 fps) and then to test condition 1 (MR 2D 60 fps). A statistically significant difference in T-thr(p,c) was observed among the 4 test conditions according to the Kruskal-Wallis test (n=20; *P*=.04). Subsequent post hoc analysis using Dunn test with Bonferroni correction revealed that only T-thr(p,1) and T-thr(p,4) are statistically significantly different, meaning that a statistically significant difference exists only between test condition 1 (MR 2D 60 FPS) and test condition 4 (direct view; n=5; *P*=.03). This analysis showed that the performance of the threading task had no significant difference between MR headset working on 3D mode and viewing directly through the eyepieces. The results also suggested that increasing the frame rate will reduce the time taken for the threading task.

Telemedicine Assessment

In the test, as depicted in Figure 5, the MR-SLP system's ability to simultaneously transmit high-resolution stereoscopic video to both local and remote MR headsets was successfully demonstrated. At the local site, the operator wearing the MR headset could simultaneously see the patient through the HMD's see-through function and view the stereoscopic examination images immersed in their real-world environment. Meanwhile, remote users connected via the internet could concentrate on the stereoscopic examination images, offering real-time expert guidance and diagnostic input, promoting effective collaboration over distances.

Figure 5. Test of mixed reality–based slit lamp (MR-SLP) for teleophthalmology. (A) The geographical relationship between the local site (Florida International University [FIU] main campus) and the remote sites (FIU Engineering Center [EC] and Bascom Palmer Eye Institute) involved in assessing image quality and user experience of the MR-SLP. (B) The images obtained directly from the camera of the MR-SLP; (C) The video frame displayed on the remote MR headset at the same time. No noticeable differences were observed between these 2 images. MMC: Modesto Maidique Campus.



During examination of the volunteer's eye with the MR-SLP, anatomical details of the anterior segment (Figure 6) were accurately captured and displayed in real time on both local and remote MR headsets. According to the ophthalmologists participating in this trial, they reported that the image quality viewed in their MR headsets closely rivaled that observed through the slit-lamp eyepieces. The real-time video streams in this trial also maintained robust depth perception and exhibited low latency at remote sites, with an average round-trip time of less than 40 milliseconds and video jitter below 20 milliseconds. This allowed for a highly interactive and collaborative examination by the local and remote ophthalmologists. Both ophthalmologists involved in the trial stated that the MR-SLP system compared favorably to traditional slit lamp viewing and highlighted its potential advantages for clinical practice.

Fundus examination using the MR-SLP was also evaluated. Following the conventional procedure, the operator, wearing the MR headset, held an ophthalmic lens (90D; Volk Optical) between the volunteer's eye and the slit-lamp objective to visualize the retina. An example result is shown in Figure 7. Under a nonmydriatic condition, different regions of the retina were clearly visualized in the headsets by adjusting the slit lamp and the Volk lens. Streaming of the fundus images to the local and remote headsets was processed at the background without interfering with the operator's performance. In the test, the operator required only a brief additional period to adapt to the hand-eye coordination. When operating from alternative positions, such as an off-axis (lateral) position, maneuvering the slit lamp and Volk lens requires establishing a new hand-eye coordination and required additional practice. However, the operator could select the operating position for fundus examination without compromising overall performance.

Figure 6. Images of the anterior segment structures captured by mixed reality–based slit lamp locally in side-by-side 3D format. (A) Iris, (B) corneal cross-section (blue stripe), (C) conjunctiva, and (D) lens. (E-H) Images in red-cyan stereoscopic format demonstrate the 3D view that can be observed using red-cyan anaglyph 3D glasses.

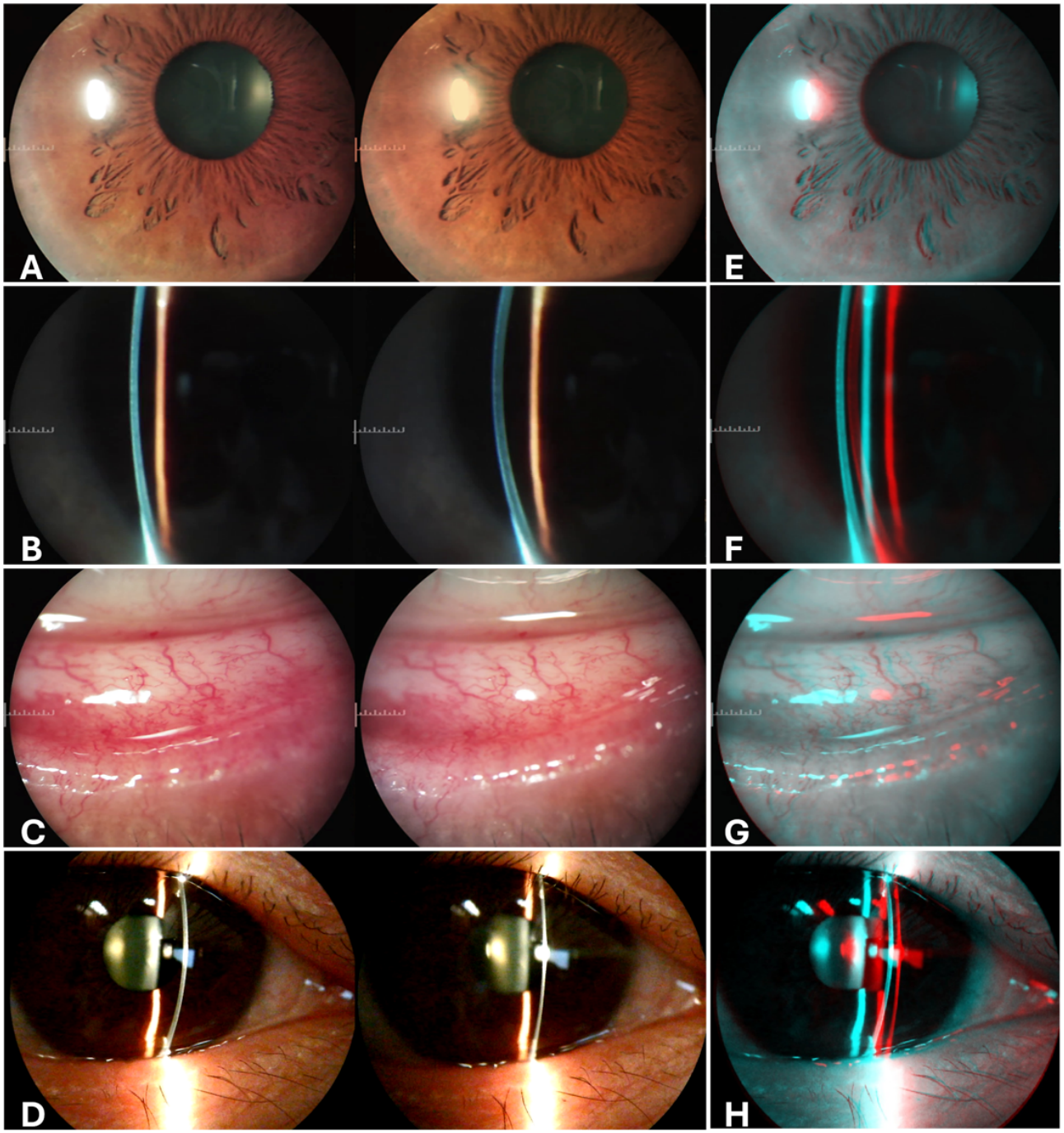
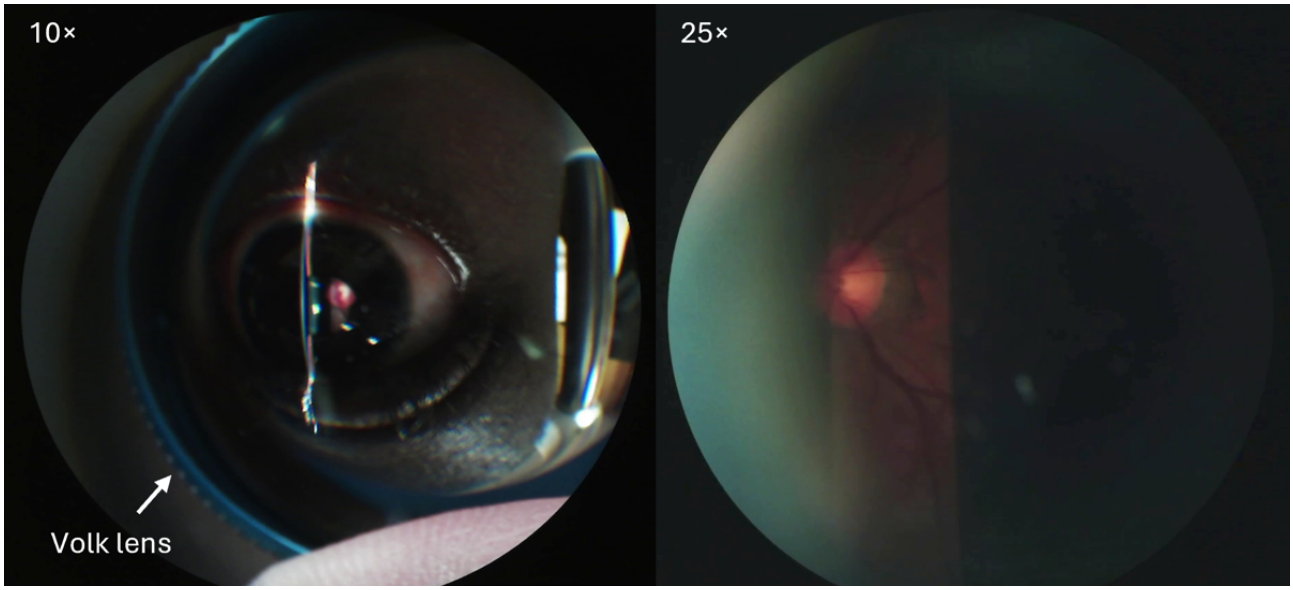


Figure 7. Fundus examination using the mixed reality–based slit lamp. Images were acquired through a handheld 90D Volk lens, showing retinal regions under a nonmydriatic condition at different optical magnifications.



Discussion

Principal Findings

We tested the performance and validated the feasibility of the MR-SLP for providing stereoscopic slit-lamp views of the eye, including the anterior segment and the fundus, in real time both locally and remotely. The MR-SLP may provide a new approach for slit-lamp examinations by eliminating the need for continuous close viewing through the eyepieces, which may offer more comfort for both the operator and the patient during examinations and more flexibility in operating the machine. Furthermore, the system enhances the efficiency of slit-lamp training by enabling multiple participants to view real-time, stereoscopic diagnostic images as if viewing them directly through the eyepieces. The remote ophthalmologist wearing the MR headset gains an immersive experience as if operating the slit lamp directly, facilitating stereoscopic teleophthalmology.

Factors Affecting Spatial Resolution

The MR headsets used in this study have a display resolution of approximately 2K per eye, while the cameras have a maximum resolution of 4K. The measured spatial resolution was similar (102 line pairs/mm) for both the images acquired by the MR-SLP cameras and the MR device, suggesting that at the tested magnification (25×) the system's effective resolution was limited by the slit-lamp optics. It is also possible that the MR device's rendering algorithms enhance the perceived clarity in the region of interest, compensating partially for the lower display pixel density [15]. However, the participants in the subjective evaluation test noted a difference in perceived clarity between the MR headset and direct eyepiece view. Since this observation was based on anecdotal reports from a small group of participants (n=3), future research should implement a larger psychophysical study to statistically quantify and validate any differences in perceived image quality.

Depth Perception, Effective Resolution, Frame Rate, and Latency

Accurate depth perception through the slit lamp is essential for precise clinical diagnosis and surgical procedures [16]. Our camera adapter and calibration algorithm allow fine-tuning of the camera position to precisely match the slit-lamp view with the digital camera view, ensuring consistent spatial mapping. The tube-threading test suggests that the MR-SLP in 3D mode may offer depth perception comparable to that of viewing through the eyepieces. Under test condition 1, participants reported that the main challenge was aligning the wire with the orifice of the tube without stereoscopic cues. A low frame rate also exacerbated the issue by creating mistiming between visual feedback and motion control, which increased the difficulty of the task. Additionally, while all participants completed a brief acclimation session, the study did not formally assess the learning curve for using the MR-SLP system. However, this preliminary test is valuable for the design of a more definitive, larger-scale validation study.

All the participants stated that the resolution target and tubes appeared clearer when viewed directly through the eyepieces. We believe this was caused by the effective resolution of the cameras used in this study during video streaming. The output frame rate was set at 60 fps only when the camera was operated at a resolution of 720p, which was limited by the camera hardware. This hardware bottleneck resulted in lower resolution of the streamed video than the slit lamp's optics and the MR headset display could provide. This issue can be resolved by using cameras that provide 1080p or higher video resolutions at a frame rate of 60 fps, which are abundant in today's market. The results of the tube-threading study, shown in Figure 4, also indicate that a higher frame rate led to better performance. This improvement may be attributed to the reduction of the motion blur at higher frame rates [17]. Future studies should explore how to best balance maintaining high frame rates with achieving higher resolutions, such as 1080p or 4K, for these dynamic procedural tasks. We believe that by introducing higher-quality

cameras and more advanced MR headsets, such as the Apple Vision Pro, the video quality of the MR-SLP at both local and remote sites will more closely match viewing through the eyepiece of a slit lamp.

System latency is a crucial factor in real-time applications, such as telemedicine, because delays can significantly impact the local operator's performance and diminish the quality of remote interactions. Latency can arise from network transmission, data processing, and display rendering [18]. While acceptable latency thresholds for demanding applications such as telesurgery are suggested to be below 100 to 200 milliseconds [19,20], platforms using WebRTC architecture can potentially achieve very low media transmission delays [21]. Remote tests conducted within the same city demonstrated a good performance with an average round-trip time of less than 40 milliseconds. Nevertheless, further evaluation through long-distance remote testing is needed.

MR Headset Challenges

In the current implementation of the MR-SLP system, Meta Quest 3 is used as the MR headset for both the local and remote locations. Quest 3 offers advantages for biomedicine applications, including high-resolution displays and advanced color pass-through that enable detailed 3D visualization of anatomical structures. The see-through function and accurate spatial mapping facilitate natural interaction and situational awareness, allowing users to seamlessly integrate virtual content with the real clinical environment. Additionally, Quest 3's onboard processing power efficiently converts side-by-side images into immersive 3D views, supporting real-time telemedicine and collaborative workflows. However, the headset's ergonomics and comfort remain suboptimal, particularly during prolonged use, such as continuous wear for more than 60 minutes. While the display resolution is high, further improvements—such as 4K or higher per eye—would be beneficial for even greater image clarity. We are also investigating alternatives to Quest 3, such as Apple Vision Pro, or augmented reality glasses. Our system's architecture is compatible with other extended reality platforms such as augmented reality for the local applications and virtual reality for remote physicians.

Limitations and Future Studies

While the technique holds promise for enhancing slit-lamp examinations, teleophthalmology, and medical training, several key limitations of our study need to be acknowledged, such as small sample size for statistical analysis and subjective evaluation based on anecdotal reports.

In this study, we did not evaluate the learning curve for different operators associated with adapting to the MR-SLP view, including potential differences in hand-eye coordination during complex maneuvers. For the evaluation of user experience with the MR-SLP, feedback from participating ophthalmologists was collected through verbal reports rather than using a validated assessment scale. Although this approach provided valuable initial insights for a feasibility study, it did not allow for quantitative analysis of user satisfaction or formal measurement of interrater agreement regarding the system. Future studies should use validated questionnaires to enable a more robust evaluation of the system's usability and acceptance in clinical settings. Additionally, the camera adapter and software implementation are cost-effective and require minimal modification, allowing for versatile integration with most slit lamps and potentially other binocular microscopes.

Conclusions

This study demonstrated the technical feasibility of the MR-SLP in capturing and transmitting real-time, stereoscopic slit-lamp examination videos to MR headsets. Our tests showed that the system can provide visuomotor performance comparable to direct viewing, and it provided low-latency streams for effective remote collaboration.

Acknowledgments

The authors attest that generative artificial intelligence was not used in the generation of any part of this manuscript.

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Data Availability

The summarized data generated during this study are included in this published article and its multimedia appendix. The full raw datasets are available from the corresponding author on reasonable request.

Authors' Contributions

Conceptualization: SJ, RZ
Data curation: RZ
Formal analysis: RZ, WCL, SJ
Investigation: RZ, SJ, WCL, BLL, RW, NA
Resources: SJ
Writing–original draft: RZ, WCL, SJ
Writing–review and editing: RZ, WCL, SJ

Conflicts of Interest

None declared.

Multimedia Appendix 1
Time required for the tube-threading tasks and picture of mixed reality–based slit lamp operation.
[DOCX File, 204 KB - xr_v3i1e93513_app1.docx]

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Abbreviations

fps: frames per second

HMD: head-mounted display
IRB: institutional review board
MR: mixed reality
MR-SLP: mixed reality–based slit lamp
WebRTC: Web Real-Time Communication

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Predictive Factors of Augmented Reality–Based Clinical Task Performance Among Novice Users: Cross-Sectional Quantitative Study

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Abstract

Background: Augmented reality (AR) can provide risk-free training for medical trainees, yet little is known about which learner characteristics facilitate adoption or inform training design.

Objective: We aimed to identify which learner characteristics predict AR performance in novices. We hypothesized that higher visuospatial ability and greater video game experience would be associated with faster completion times and fewer errors.

Methods: In this cross-sectional study, 21 undergraduate, graduate, and medical students (median age 22, IQR 21-24 years) without previous AR experience were recruited between June and December 2024. Participants completed a technology experience survey, the mental rotation task (MRT) for visuospatial ability, a standardized 7-task AR protocol mimicking clinical use on the Microsoft HoloLens 2 (hologram manipulation, orbit tracing, anatomical plane visualization, and hologram-to-object registration), and the National Aeronautics and Space Administration Task Load Index for cognitive load assessment. Outcome measures included completion time, slips (unintentional errors), and tracing quality.

Results: All analyses used a significance of α=.05. MRT scores did not predict baseline performance time (Pearson r=0.15, 95% CI −0.32 to 0.55; P=.54) or error rates (r=0.18, 95% CI −0.27 to 0.57; P=.43). Participants with extensive video game experience (>5 hours/week) made fewer slips (unpaired t test; mean difference −2.62 slips, 95% CI −5.19 to −0.04; P=.047), without faster completion times (Mann-Whitney test; median difference −22 seconds, 95% CI −7.00 to 57.00; P=.24). Video game experience did not predict baseline performance time (Pearson r=−0.35, 95% CI −0.69 to 0.13; P=.14). Significant learning effects emerged in unadjusted analyses: completion times decreased on attempts 2 and 3 compared with attempt 1 (mixed-effects analysis: mean difference 28.75 seconds, 95% CI 12.98-44.52; P<.001; 28.00 seconds, 95% CI 10.75-45.25; P=.002, respectively) with fewer slips (Friedman test: χ^2_2=17.8; P<.001; Dunn post hoc: P=.008 and P<.001, respectively). Orbit tracing (Wilcoxon test: median difference −5 seconds; P=.004) and virtual landmark placement times improved (Friedman test: χ^2_3=14.6; P=.002; Dunn post hoc; P=.009 and P=.02), but physical landmark placement did not. Covariate-adjusted models revealed no significant trial-by-covariate interactions.

Conclusions: Visuospatial ability does not predict clinically relevant AR performance, while extensive video game experience was associated with fewer errors. Despite previous studies emphasizing inherent learner characteristics in laparoscopy and endoscopy, covariate-adjusted models showed that AR learning curves were not significantly modified by MRT or video game experience. These findings suggest that early AR performance improvements among novice users are primarily driven by learning rather than visuospatial ability, supporting training approaches that emphasize structured practice, although the modest sample size limits detection of smaller effects.

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KEYWORDS

mixed reality; augmented reality; virtual reality; mental rotation task; visuospatial ability; medical education; video games

Introduction

The rise in augmented reality (AR) and virtual reality (VR) technology has greatly impacted a range of industries, including education, entertainment, and medicine [1,2]. AR enables the supplementation of real-world visibility with digital information, which can be shown through projections onto head-mounted displays (HMD) on headsets, smart glasses, or tablet-based displays. Within medicine, AR and VR applications continue to grow. While outcomes research remains preliminary given AR's relative infancy, studies have found that AR subjectively increases surgeon confidence in delineating tumor margins [3]. This observation was validated by a multicenter randomized controlled trial (n=113), which observed that AR-guided robotic prostatectomies were associated with a significant decrease in subsequent positive surgical margins, a key prognostic indicator for patient survival [4]. Other measured improvements have included decreased fluoroscopy time needed to navigate difficult tissue structures [5,6]. This technology has also expanded patient education [7,8] by helping patients gain a deeper understanding of their bodies and diseases while also demonstrably decreasing procedural anxiety [8,9] and improving satisfaction [8].

As applications of AR and VR continue to expand across specialties, these technologies hold tremendous potential as risk-free training modalities, allowing medical students and resident physicians to practice procedures without jeopardizing patient safety [10]. Recent literature has shown that AR can help resident physicians learn to identify aneurysms in surgical videos [11], support medical student and resident education as a reliable and predictive simulation-based medical education modality [12-14], and minimize mental workload while simultaneously improving learning capacity [15,16].

Despite this promise, there are still some important factors to consider. Although previous studies indicate that AR can increase mental resource availability [15], enhance working memory capacity [16], and facilitate long-term information storage [16], it may also serve as a distraction for some learners [17]. Research has shown broad educational benefits, from early childhood learning in preschool [18] to secondary education [19] and postgraduate medical education [13]. However, the extent of AR integration in medical education remains varied [20].

Within medical education specifically, previous studies have indicated mixed learning outcomes. For example, AR can be beneficial for anatomy learning compared to virtual dissection tables, but not when compared to the conventional atlas method [21]. Similarly, other studies have found no difference in learning among stereoscopic 3D AR models, monoscopic 3D desktop models, or conventional atlas learning [17]. Further complicating its role, evidence suggests that individuals who have lower spatial ability, as measured by mental rotation tasks (MRTs), may benefit more from AR than their peers with higher MRT scores [21,22]. These findings indicate that the mixed effects of AR within medical education may be explained by individual differences in spatial ability.

Despite the importance of spatial ability across industries, including STEM [23-25] (science, technology, engineering, and math) and medicine [26-29], and the growing adoption of AR within medicine [30], there is still a critical gap in our understanding of how novice AR users learn to use the technology. Previous experiences, such as video game experience, have been shown to play a role in spatial ability [31] as well as in medically relevant tasks [32,33]. More recently, studies have demonstrated that video game experience is a strong predictor of baseline skills in gastrointestinal endoscopy learners [34] and of baseline performance in nonmedical VR tasks [35].

However, it remains unclear which learner characteristics (eg, visuospatial ability and previous video game experience) support the efficient adoption of AR in clinical applications and whether short, targeted exposure is sufficient for novice users to reach proficiency. This study addresses this gap by quantifying novice performance and short-term learning on a neurosurgical AR navigation task and examining how these outcomes relate to individual differences in mental rotation ability and video game experience. We hypothesize that individuals with higher visuospatial ability and, specifically, more video game experience will complete AR-based neurosurgical navigation tasks more quickly and with fewer errors. These results may indicate whether specific learner characteristics confer an advantage in AR or whether novice performance in AR is primarily influenced by learning.

Methods

Research Design

This study used a cross-sectional framework in which participants were recruited using convenience sampling to complete a pretest demographics survey and an assessment of visuospatial ability, followed by a series of standardized AR tasks and a posttest National Aeronautics and Space Administration Task Load Index (NASA-TLX) survey to assess subjective mental load. This paper was prepared in accordance with the Journal Article Reporting Standards [36].

Inclusion and Exclusion Criteria

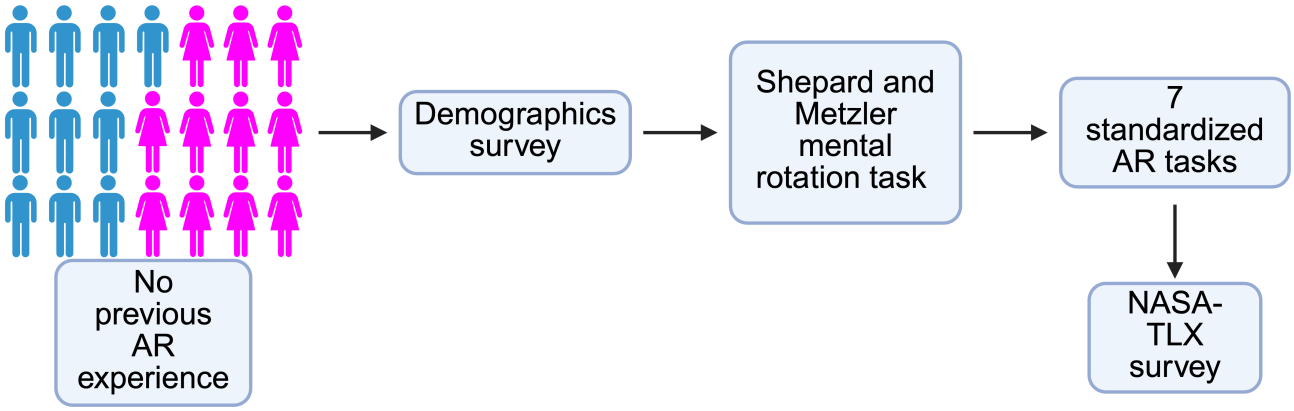
Participants comprised undergraduate, graduate, and medical students at the University of Pittsburgh between June 2024 and December 2024. Participants who had previous experience using AR were excluded.

Ethical Considerations

Participants gave their informed consent for participation in the study, for their performance to be recorded for analysis, and for any secondary analyses without additional consent. Participants were not compensated. The authors confirm that there are no images or identifiable features within this manuscript. All participant information was deidentified, and study data were

stored in an encrypted location. This study received institutional review board approval from the University of Pittsburgh (STUDY22040182). The study workflow is shown in Figure 1.

Figure 1. Study design. In total, 23 participants were recruited for this study between June 2024 and December 2024. Two participants did not successfully complete all tasks and were excluded from the analysis, resulting in a final cohort of 21 participants. There were 11 female (pink) and 10 male (blue) participants with no previous experience with augmented reality (AR). The demographics survey collected information such as experience with video games, comfort with new technology, and educational background. All participants then performed a series of mental rotation tasks before completing 7 standardized AR tasks. Following completion of the tasks, participants were given a posttest National Aeronautics and Space Administration Task Load Index (NASA-TLX) survey to assess workload.



Surveys

Two pretest tasks were administered. The first task was a survey that collected demographic and experience information such as age, sex, level of education, experience with video games, comfort with new technology, and experience with surgical devices. The second pretest task was the MRT, a standardized paper-and-pencil measure of 3D spatial visualization derived from the mental rotation paradigm by Shepard and Metzler [37]. The MRT requires participants to decide whether comparison figures are rotated versions or mirror images of a target 3D object, providing a robust index of individual differences in mental rotation ability. Classic psychometric work has shown that the MRT has high internal consistency as indicated by the Kuder-Richardson Formula 20 (Kuder-Richardson Formula 20=0.88), which estimates how consistently dichotomously scored items measure the same underlying construct. Classic psychometric work has also demonstrated that the MRT has high test-retest reliability (r=0.83) [38], and subsequent reviews describe it as one of the most commonly used and well-validated measures of spatial ability [39,40]. Moreover, mental rotation tests such as the MRT are routinely incorporated into spatial ability batteries and reliably predict performance in applied visuospatial tasks (eg, engineering design, navigation, and surgical endoscopy) [29,41,42]. Because our experimental tasks required participants to infer 3D relationships from 2D displays and mentally transform object orientations, we selected the MRT as the primary measure of visuospatial ability.

This task was composed of 2 sets of 12 problems. Participants were allotted 3 minutes to complete each set of questions. During this task, participants were given a warning when their remaining time reached 2 minutes, 1 minute, 30 seconds, and 10 seconds. Following AR testing, participants were given the NASA-TLX survey, a clinically validated metric for measuring mental load [43].

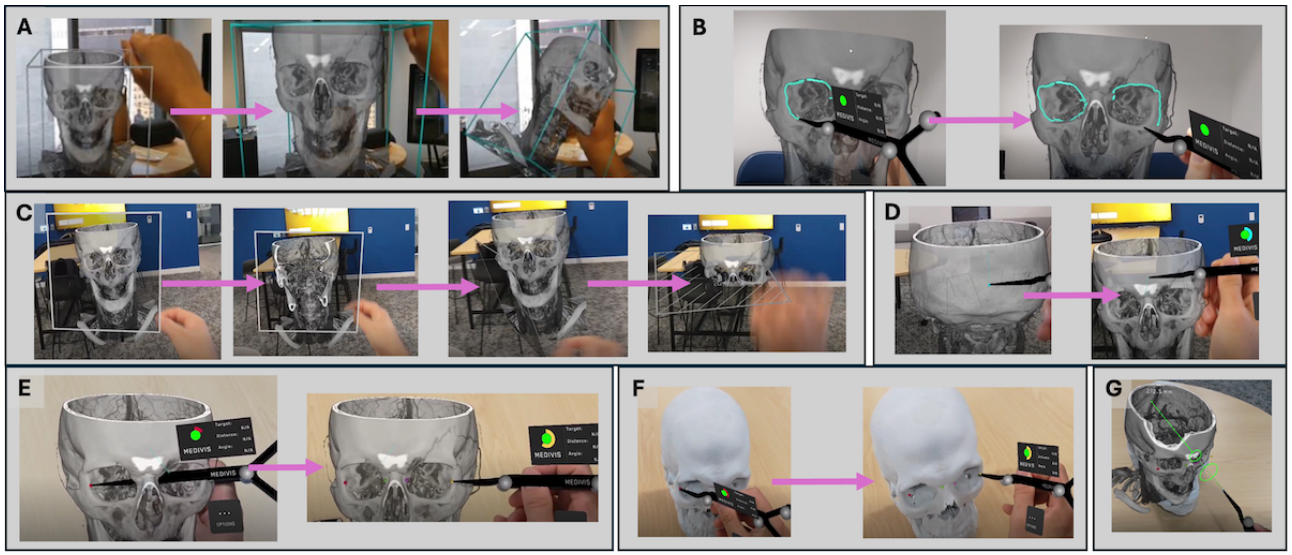
Experimental Procedure

This study conducted AR-based tasks using SurgicalAR (version 1.6.1; Medivis Inc) software on Microsoft HoloLens 2. SurgicalAR is a surgical guidance system that volumetrically renders Digital Imaging and Communications in Medicine data and projects it onto an HMD, allowing for direct registration to patients. Participants were shown a generic, deidentified computerized tomography angiogram of the head. For tasks that required a stylus or pointer, a stylus tracked by the SurgicalAR system was used.

Participants were given 7 different AR-based tasks that were deliberately selected to resemble the clinical workflow steps that a neurosurgeon would perform in the operating room. Specifically, tasks 1 to 3 mimicked basic hologram interactions that may be performed while visualizing key structures or planning an operative approach. Tasks 4 to 7 were designed to follow a standard hologram-to-object registration in which 4 corresponding points were placed on the hologram and the physical object. Then, a 3D transformation was computed using the method by Horn [44] to complete the registration.

Before participants began using AR, the study moderator demonstrated the task using the HoloLens 2 while participants viewed the task through the SurgicalAR system cart monitor, which was positioned near the moderator. Then, the moderator gave and adjusted the headset on each participant and instructed them on basic gesture interactions. All tasks were performed on and recorded using the HoloLens 2. Videos were analyzed for performance using predefined metrics, as defined below. A description of each task is provided below, and representations of the tasks can be seen in Figure 2.

Figure 2. Series of augmented reality tasks that participants were required to complete. (A) Baseline performance: resizing and rotating a hologram of a human skull model; (B) orbit tracing: outlining the orbital rims on the hologram; (C) plane visualization: viewing coronal, sagittal, and axial planes of the hologram; (D) anterior-posterior trajectory point: placing virtual trajectory markers on the hologram; (E) virtual landmark placement: placing 4 virtual landmarks on the hologram; (F) physical landmark placement: placing 4 physical landmarks on the 3D-printed human skull model; and (G) trajectory alignment: performing trajectory alignment.



- Task 1 (Figure 2A): participants resized and rotated a hologram of a human skull model. This task required participants to unanchor the hologram, detaching it from its fixed position and allowing free movement. They then needed to make the hologram larger (zoom in) and smaller (zoom out) and rotate the hologram 360°. Finally, participants reanchored the hologram, locking it back into its original orientation and size. This task was repeated 3 times. Task performance was measured by time taken to complete and by number of slips. Slips were defined as unintentional errors or mistakes [45,46].
- Task 2 (Figure 2B): participants outlined the orbits (eye sockets) of the hologram. Participants were instructed to perform the orbit tracing in one continuous motion for each orbit, without retracting the areas they had already outlined. Performance was measured by a qualitative analysis of orbit tracing quality.
- Task 3 (Figure 2C): participants moved a cut-plane tool fully through the hologram of computerized tomography angiogram of the head in 3 directions—coronal, sagittal, and axial. They were instructed to perform the task while keeping their body facing the front of the hologram. Performance was measured by the number of slips, defined as instances in which a person intends to do one action but unintentionally does something else [45,46].
- Task 4 (Figure 2D): participants placed 2 virtual trajectory landmarks. The first point was placed midline on the lambdoid suture, and the second point was placed midline on the frontal bone. Performance was measured by the time required to successfully place the posterior point and anterior point.
- Task 5 (Figure 2E): participants placed 4 virtual landmark points on the bilateral lateral and medial parts of the hologram's orbit. They began with the lateral left orbit and worked from left to right, finishing with the lateral right orbit. Performance was measured by the time to place each virtual landmark point.
- Task 6 (Figure 2F): participants placed 4 physical landmark points on a 3D-printed skull model, matched to the same locations as the virtual landmarks. They began with the lateral left orbit and worked from left to right, finishing with the lateral right orbit. Performance was measured by the time to place each physical landmark point.
- Task 7 (Figure 2G): participants registered the holographic computerized tomography projection onto the physical skull and then activated the trajectory alignment tool. To accomplish this, participants used the stylus to make the anterior-posterior trajectory turn green, indicating successful alignment. Performance was measured by time taken to align trajectory.

Statistics

Descriptive statistics were used to summarize demographic variables and baseline characteristics. Group comparisons were performed using independent samples 2-tailed *t* tests for continuous variables and Pearson χ^2 tests for categorical variables, where appropriate. To assess learning effects, mixed-effects models with Tukey multiple comparisons were used for completion times. Friedman tests with Dunn post hoc comparisons were used for error counts and landmark placement times, and Wilcoxon signed-rank tests were used for paired comparisons. The overall effect of trial on performance was evaluated using a 1-way repeated-measures ANOVA with Greenhouse-Geisser correction. To evaluate whether learning effects were modified by MRT scores or video game experience, a covariate-adjusted repeated-measures general linear model was used. Linear regression was used to evaluate the predictive relationship between MRT scores and baseline task performance. Participants were stratified based on video game experience (>5 hours/week vs ≤5 hours/week) to assess group differences in task outcomes. Significance was set at α=.05 for all comparisons. All statistical analyses were conducted using GraphPad Prism (version 10.0.0; GraphPad Software Inc).

Results

Overview

In total, 23 participants with no previous experience with AR were recruited for this observational study. Of these, participants 3 and 42 (8.69%) did not successfully complete all tasks and were excluded from the analysis, resulting in a final cohort of 21 (91.3%) participants. Within the final cohort, there were 11 (52.4%) female participants, and the median age was 22 (IQR 21-24) years. There were 15 (71.4%) participants who were undergraduate students. In total, 13 (61.9%) participants spent between 0 to 5 hours per week playing video games, and 10 (47.6%) participants spent between 0 to 10 hours per week interacting with a touch screen device or computer. Furthermore, 13 (61.9%) participants were completely comfortable with new technology. Specific demographic information and comfort with new technology are presented in Table 1. Results of the NASA-TLX are presented in Table 2.

Table . Participant demographics (N=21).

Variable	Value
Sex, n (%)	
Female	11 (52.4)
Male	10 (47.6)
Age (years), median (range; IQR)	22 (19-25; 21-24)
Level of training, n (%)	
Undergraduate student	15 (71.4)
Medical student	5 (23.8)
Master's student	1 (4.76)
Time spent playing video games per week (hours), median (range; IQR)	5 (0-55; 1.5-21)
Weekly video games use (hours), n (%)	
0-5	13 (61.9)
6-10	1 (4.76)
11-15	2 (9.52)
16-20	0 (0)
≥21	5 (23.8)
Time spent interacting with touch screen device or computer (hours), median (range; IQR)	15 (0-63; 5-40)
Weekly touch screen devices or computer use (hours), n (%)	
0-10	10 (47.6)
11-20	1 (4.76)
21-30	3 (14.3)
31-40	3 (14.3)
≥41	4 (19.0)
Comfort with new technology (scale 1-5), n (%)	
Totally comfortable (5)	13 (61.9)
Very comfortable (4)	4 (19.0)
More or less comfortable (3)	3 (14.3)
Not very comfortable (2)	1 (4.76)
Not comfortable at all (1)	0 (0)
Experience with other forms of surgical guidance, n (%)	
Endoscopy[a]	2 (9.52)
DaVinci[b]	1 (4.76)
Microsurgery	0 (0)

[a]Average experience with endoscopy was 13 (SD 4.49) hours.

[b]Total experience with DaVinci was 6 hours.

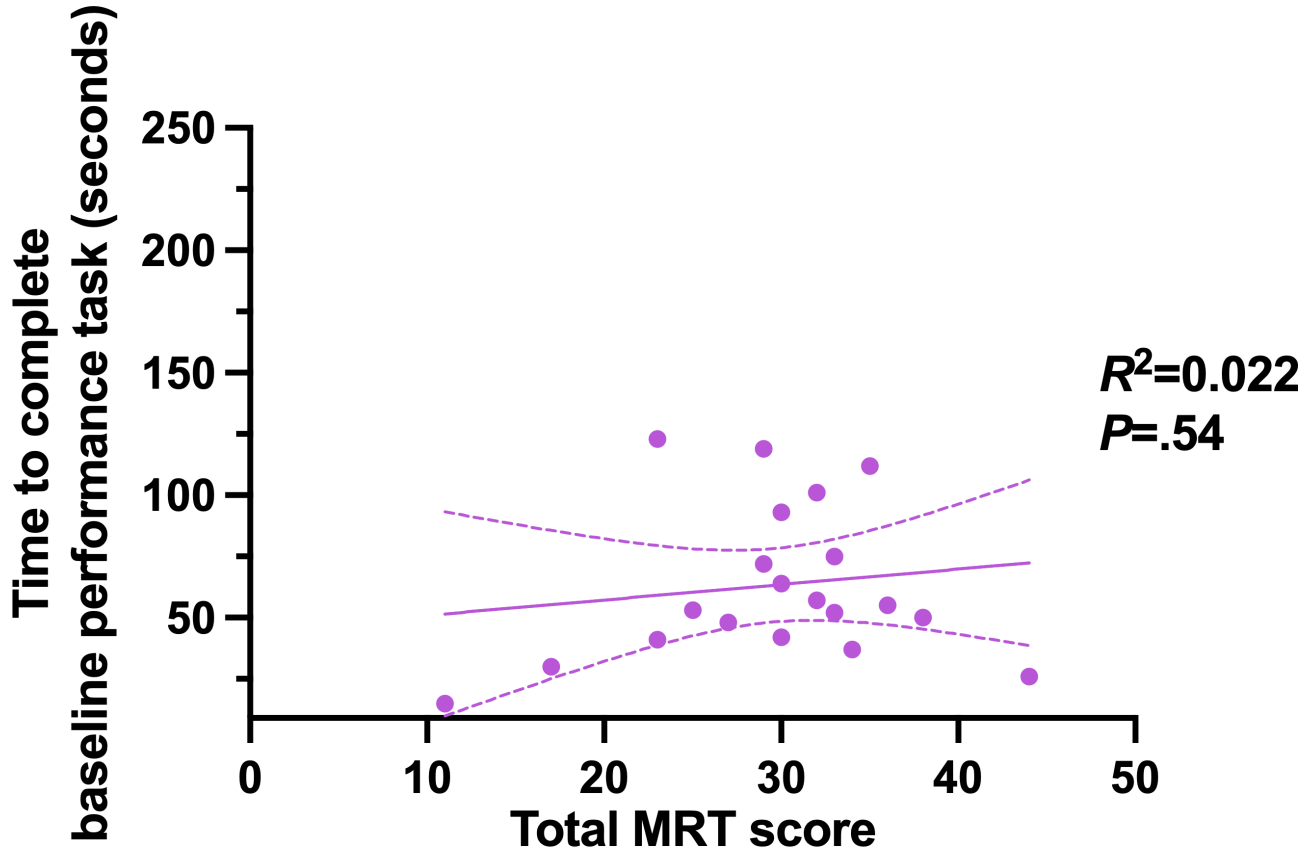
Table . National Aeronautics and Space Administration Task Load Index scores.

Category	Value, median (range; IQR)
Mental demand	50 (0-80; 25-67.5)
Physical demand	15 (0-70; 5-30)
Temporal demand	35 (0-75; 10-50)
Performance (lower is better)	50 (20-85; 37.5-67.5)
Effort	50 (0-90; 30-67.5)
Frustration	30 (0-85; 12.5-60)

Overall Performance on MRT

Visuospatial ability, as measured by the MRT, did not predict the time taken to complete the baseline performance task (Pearson r=0.15, 95% CI −0.32 to 0.55; R^2=0.022; P=.54; Figure 3). Similarly, MRT scores did not predict error rates on the baseline performance task (r=0.18, 95% CI −0.27 to 0.57; R^2=0.034; P=.43). There were no statistically significant differences in baseline performance time (P=.65) or number of slips (P=.62) between individuals with MRT scores ≥30 and those with scores <30.

Figure 3. Association between visuospatial ability, measured by the mental rotation task (MRT), and baseline task completion time. Each dot represents an individual participant's MRT score and corresponding completion time. The solid line indicates the linear regression fit, and the dashed lines represent the 95% CI of the regression. MRT score does not predict the ability to complete the baseline performance task (R^2=0.022; P=.54).



Video Game Performance

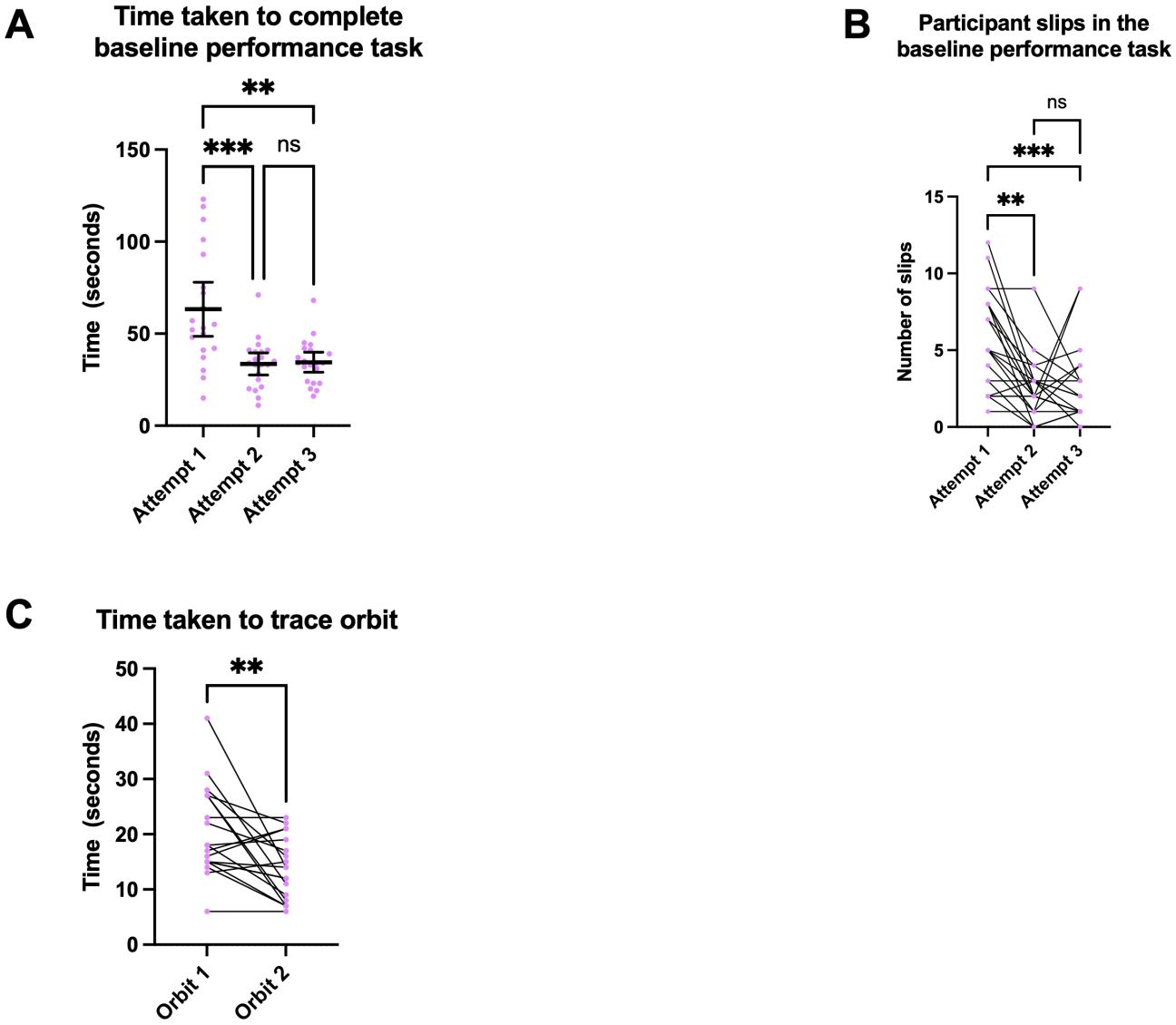
Participants were split into 2 groups based on video game experience (group with "extensive" experience of >5 hours/week and group with "minimal" experience of ≤5 hours/week) for analysis. This distribution was determined empirically to yield approximately equal participants per group (8 and 13, respectively). Participants with extensive video game experience did not demonstrate faster completion times compared to those with minimal video game experience (Mann-Whitney test; median difference −22 seconds, 95% CI −7.00 to 57.00; P=.24). However, individuals who had extensive video game experience made fewer slips on average than those who had minimal video game experience (mean 4.00, SD 2.27 slips, 95% CI 2.10-5.90 vs mean 6.61, SD 3.36 slips, 95% CI 4.59-8.64; unpaired t test; mean difference −2.62 slips, 95% CI −5.19 to −0.04; P=.047).

Learning

Participants learned to perform the baseline performance task (task 1) in a significantly shorter time between attempts 1 and 2 (mean 63.3, SD 31.4 seconds, 95% CI 48.5-78.0 vs mean 33.6, SD 13.1 seconds, 95% CI 27.6-39.6; P<.001) and attempts

1 and 3 (mean 63.3, SD 31.4 seconds, 95% CI 48.5-78.0 vs mean 34.5, SD 12.0 seconds, 95% CI 29.0-40.0; *P*=.002), but not between attempts 2 and 3 (mean 33.6, SD 13.1 seconds, 95% CI 27.6-39.6 vs mean 34.5, SD 12.0 seconds, 95% CI 29.0-40.0; *P*>.99; Figure 4A).

Figure 4. Learning effects observed across various augmented reality tasks. (A) Time taken to complete baseline performance task across attempts. Each dot represents an individual participant, and the horizontal lines indicate the mean with 95% CIs. Participants performed the baseline performance task in a significantly shorter time between attempts 1 and 2 [***P*<.001] and attempts 1 and 3 [***P*=.002]. The comparison between attempts 2 and 3 was not significant [ns; *P*>.99]. (B) Number of slips in the baseline performance task across attempts. Each dot represents an individual participant, and the connecting lines track each participant's performance across attempts. Participants improved in the accuracy of completing the baseline performance task, as demonstrated by fewer slips between attempts 1 and 2 [***P*=.008] and attempts 1 and 3 [****P*<.001]. The comparison between attempts 2 and 3 was not significant [ns; *P*>.99]. (C) Time taken to trace orbits. Each dot represents an individual participant, and the connecting lines track each participant's performance between orbits. Participants significantly improved the time to trace the orbits on the second attempt [***P*=.004].



A 1-way repeated-measures ANOVA indicated that there was a significant effect of trial time, consistent with improved performance across trials (Greenhouse-Geisser $F_{1.135,22.691}$=11.890; *P*=.002). However, a covariate-adjusted repeated-measures general linear model that included weekly gaming hours and MRT score indicated that the trial effect was not significant (Greenhouse-Geisser $F_{1.112,20.021}$=0.050; *P*=.85), and there was no evidence that trial-related changes depended on either covariate (trial×gaming hours: *P*=.62; trial×MRT: *P*=.34).

In addition to faster task completion times between attempts 1 and 2 and 1 and 3, participants also performed the task more accurately. There was a decrease in the number of slips between attempts 1 and 2 (mean 5.62, SD 3.2 slips, 95% CI 4.2-7.1 vs mean 2.48, SD 2.02 slips, 95% CI 1.6-3.4; *P*=.008) and attempts 1 and 3 (mean 5.62, SD 3.2 slips, 95% CI 4.2-7.1 vs mean 2.57, SD 2.52 slips, 95% CI 1.4-3.7; *P*<.001; Figure 4B). Furthermore, participants completed the orbit tracing more quickly between the first and second orbit (mean 20.4, SD 8.15 seconds, 95% CI 16.5-24.4 vs mean 13.9, SD 5.52 seconds, 95% CI 11.31-16.5; *P*=.004) without a change in quality of orbit tracing (*P*=.77; Figure 4C).

Additionally, participants required less time to place virtual landmark points 2 and 3 (mean 7.2, SD 4.82 seconds, 95% CI

5.0-9.4 vs mean 4.2, SD 1.81 seconds, 95% CI 3.4-5.0; *P*=.009) and points 2 and 4 (mean 7.2, SD 4.82 seconds, 95% CI 5.0-9.4 vs mean 4.0, SD 1.82 seconds, 95% CI 3.2-4.8; *P*=.02). There was no learning effect observed for placing physical landmarks (Friedman test; Dunn post hoc: all pairwise *P*≥.64). There was no significant difference in the learning curve between participants with MRT scores ≥30 and those with scores <30 (*P*=.87). Furthermore, there was no difference in learning curves between participants with extensive video game experience and those with minimal video game experience (*P*=.81).

Predictive Variables

MRT performance did not predict baseline performance, as measured by task 1 (*P*=.54; Figure 3). Additionally, video game experience was not a predictor of baseline performance (Pearson *r*=−0.35, 95% CI −0.69 to 0.13; R^2=.12; *P*=.14); however, it did predict the number of slips (*P*=.046).

Discussion

Principal Findings

As AR technology continues to improve and integrate within health care and other industries, it becomes increasingly important to understand which factors contribute to technological proficiency among novice AR users. By identifying these factors, product designers can address the scarcity of implementation models that is hindering the widespread adoption of AR and VR in clinical settings [30] and develop programs to help guide novice users through more complex AR-based interactions, thereby proactively addressing areas of difficulty, minimizing the user learning curve, and increasing user adoptability. To address this growing need, our study aimed to identify predictors of performance in novice AR users. Our findings suggest that visuospatial ability does not predict AR task completion time, though extensive video game experience was associated with greater accuracy. Despite this result, neither visuospatial ability nor video game experience corresponded with an improved learning curve.

Predictive Variables of Performance Gains

Existing literature has placed a strong emphasis on visuospatial ability as a predictor of performance in various clinical settings, including ultrasound [27], laparoscopic [28], and endoscopic procedures [29], as well as in nonclinical settings [47,48] and learning [26]. Given that factors such as depth perception and stereovision undoubtedly contribute to an individual's visuospatial ability [49], our study used one of the most popular validated ways of evaluating spatial ability, the MRT [50,51]. In our study, we found no relationship between MRT scores and baseline performance. This suggests that AR proficiency may be influenced by more nuanced visual processing skills that are not captured by the MRT.

Höhler et al [49] and Martin-Gomez et al [52] have suggested that depth perception and stereoacuity affect individuals' ability to estimate distances of objects in AR. Given the importance of interacting with virtual elements in AR, estimating the depth and position of these objects may play a larger role than previously thought and could account for the visual processing skills that are not captured by the MRT.

The observed result that increased video game experience was correlated with increased accuracy in AR tasks may be explained by the beneficial effect of gaming on spatial cognition. Work by Bavelier and Green [53] indicates that specifically action video game play enhances spatial cognition; however, other literature has indicated that these cognitive improvements are not unique to only action games [54]. This indicates that the relationship between video game experience and accuracy in AR may be due to the cognitive benefits of extensively playing video games, regardless of genre.

The literature indicates that video game experience may be a positive predictor of performance in surgical tasks with respect to errors and time [55-57]. Our findings suggest that this relationship may extend to AR-based applications with respect to errors; however, more research is needed to evaluate its effect on performance time.

Learning How to Use AR

One of the reasons AR can be challenging for novice users is the variability in the learning process [58]. However, as with other skills, increased AR exposure is associated with improved performance. Our unadjusted analyses demonstrated a rapid learning effect, with the most pronounced gains occurring during early task exposure. This suggests that novice AR users may rapidly familiarize themselves with the AR environment. However, covariate-adjusted models did not indicate that these improvements differed significantly based on user characteristics.

Users who initially performed tasks more slowly demonstrated the greatest improvement. Tasks requiring less depth perception showed more rapid learning, while those emphasizing higher depth perception and precision, such as the virtual landmark placement (task 5), improved more gradually. Notably, physical landmark placement (task 6) did not show a learning effect, possibly because participants could rely on tactile feedback from touching the skull with the stylus.

Given that covariate-adjusted models showed no significant influence of MRT or video game experience on learning, these findings suggest that inherent user characteristics, such as spatial ability, do not impact early AR learning capacity in novice users. However, given our modest sample size (N=21), the nonsignificant covariate terms and interactions should be interpreted cautiously.

Importance of Depth Perception With AR

There is a possibility that depth perception and stereoacuity play a larger role in novice AR performance due to inherent technological limitations of the HMD. The AR device used in this study, the Microsoft HoloLens 2, uses a traditional fixed plane optical display. Research with the HoloLens has supported that visual rendering factors such as shadows [59] and lighting conditions [60] may impact the depth perception of users. Additionally, binocular disparity and the occlusion of an object are other important cues for depth perception [61].

If a user attempts to interact with a virtual object in AR, they may experience an occlusion error, in which the object appears translucent despite the user's hand not being at the appropriate distance to interact with it. Uehira and Suzuki [61] identified that this depth perception error was highly varied between individuals, particularly at short distances where the difference in binocular disparity is especially pronounced. Most of the tasks in our study were performed at short distances, mimicking clinical interactions with AR. Our study did not quantify the distances of the virtual objects, nor did we measure how many times users missed targets due to misjudgment of depth. Given that interaction with virtual objects is a fundamental component of AR use, it is likely that individuals who have stronger depth perception abilities may outperform those with weaker depth perception [49].

Concurrently, these findings provide new evidence that traditional measures of visuospatial ability do not reliably predict novice AR performance, while unmeasured factors, including depth perception, may contribute more than previously thought. The early performance gains observed in unadjusted analyses suggest that novice AR proficiency can be rapidly developed, a result supported by short-format training within urology [14]. Importantly, these learning effects, combined with the scarcity of existing implementation models [30], suggest that successful AR adoption may benefit from short, targeted training programs that guide all novice users to a competency threshold rather than prioritizing users based on traits such as visuospatial ability or video game experience. Furthermore, this emphasizes that predictive measures of novice performance should be interpreted in the context of this rapid rate of improvement.

Limitations

This study has some notable limitations. The potential sampling bias introduced by the inclusion of only undergraduate and graduate students may limit the generalizability of the findings to broader populations, such as resident and attending physicians who represent actual AR users in health care settings. Given that our sample size was 21 nonsurgeon participants, we believe that further research evaluating the learning curve within intraoperative environments is necessary before concluding that task-specific guides will reduce the learning curve.

Additionally, as the sample was modest (N=21) and the covariate-adjusted model included multiple predictors (gaming hours and MRT), this study may be underpowered to detect small-to-moderate covariate effects and trial-by-covariate interactions. Accordingly, nonsignificant covariate terms (eg, gaming hours P=.80; MRT P=.17) and interaction terms (trial×gaming hours P=.62; trial×MRT P=.34, Greenhouse-Geisser corrected) should be interpreted cautiously. Additionally, video game experience was self-reported and categorized based on hours per week. Our study found it challenging to obtain the genre of video games played and therefore did not analyze whether different categories of video games influenced performance with AR. The cognitive demand effects and the type of video games were not collected; however, these factors may have an influence on how participants perform in the tasks we evaluated in this study. Furthermore, technical limitations of the Microsoft HoloLens 2 cannot be discounted, such as ambient lighting conditions in the room during experimentation, which may have affected hologram visual quality. Finally, some outcomes, such as orbit tracing quality, were evaluated qualitatively and may be subject to observer bias.

Conclusions

As AR technology continues to grow in adoption across different industries, there is an increased need to identify the factors that contribute to effective AR use. Our research found that extensive video game experience was correlated with decreased error frequency, while neither visuospatial ability nor video game experience predicted novice user performance time. We believe that future research should focus on how depth perception, stereoacuity, and learning play a role in novice user performance, while also evaluating the learning curve of surgeons in intraoperative environments. This area of research holds important promise and may shape how industry professionals and product developers design and train future users to adopt AR systems more effectively.

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Data Availability

The data presented in this study are available from the corresponding author on reasonable request and with institutional approval.

Conflicts of Interest

EGA, JTB, and GH are shareholders of SymphonyMR Inc.

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Abbreviations

AR: augmented reality
HMD: head-mounted display
MRT: mental rotation task
NASA-TLX: National Aeronautics and Space Administration Task Load Index
STEM: science, technology, engineering, and math
VR: virtual reality

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