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Contents

Review

Original Papers

Efficacy of Virtual Reality–Based Mindfulness Interventions: Systematic Review and Meta-Analysis

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Abstract

Background: Virtual reality–based mindfulness interventions (VRbMIs) increasingly populate studies as scalable tools for stress and emotion regulation. However, findings across psychological outcomes are heterogeneous, and methodological variation in intervention design, outcome measurement, and reporting practices limits cross-study comparability and cumulative synthesis.

Objective: A PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020–compliant systematic review and meta-analysis was conducted to evaluate the psychological effects of VRbMIs published between 2023 and 2025, examining methodological quality and outcome consistency across diverse study designs.

Methods: A PRISMA 2020–compliant systematic search was conducted across PubMed, PsycINFO, Scopus, Semantic Scholar, and CORE from January 2023 to April 2025. Eligible studies included quantitative VRbMIs reporting psychological outcomes. We assessed risk of bias using the Mixed Methods Appraisal Tool and conducted random-effects meta-analyses using Hedges *g* where data were sufficient.

Results: VRbMIs were associated with a large, statistically significant reduction in negative affect and a statistically significant increase in state mindfulness, while effects on depression, stress, and anxiety were small to moderate and nonsignificant. Trait mindfulness was described narratively rather than meta-analyzed and showed limited, inconsistent change across studies. For anxiety, we included 13 studies contributing 27 effect size estimates in the quantitative synthesis. A random-effects model indicated a small-to-moderate, nonsignificant pooled effect (g=0.44, 95% CI –0.08 to 0.96; t_{26}=1.74; P=.09), with substantial between-study heterogeneity (Q_{26}=381.60; P<.001; τ^2=0.96). Physiological outcomes were reported across a subset of studies and generally aligned with self-reported psychological findings; however, inconsistent measurement and incomplete reporting precluded quantitative synthesis. This analysis represents 35 studies with a combined sample of approximately 1550 participants (1 study did not report sample size).

Conclusions: VRbMIs demonstrate statistically significant short-term benefits for negative affect and state mindfulness, with consistently positive but nonsignificant trends toward improvement in stress, anxiety, and depression. Effects on positive affect and trait mindfulness were small and less consistent. Physiological findings were promising but limited by inconsistent reporting. These results support the use of VRbMIs as accessible tools for emotional regulation across diverse populations, while highlighting the need for larger trials, standardized outcome reporting, and more rigorous control conditions to strengthen the evidentiary foundation of this rapidly evolving field.

Trial Registration: PROSPERO CRD420251178827; https://www.crd.york.ac.uk/PROSPERO/view/CRD420251178827

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KEYWORDS

virtual reality–based mindfulness interventions; systematic review; meta-analysis; stress; psychological; affect; mindfulness

Introduction

Background

Mindfulness-based interventions (MBIs) have consistently demonstrated benefits for stress reduction, emotion regulation, and overall well-being across clinical and nonclinical populations [1-3]. Virtual reality (VR) technologies provide an immersive delivery modality for mindfulness interventions through multisensory environments that support sustained attention and embodied engagement. Virtual reality–based mindfulness interventions (VRbMIs) integrate contemplative instruction with 3D or 360° environments, allowing participants to practice focused attention and relaxation within simulated natural or therapeutic contexts [1,4,5]. Early evidence indicates that VRbMIs are associated with physiological markers of

regulation, including increased heart rate variability (HRV) and alpha electroencephalography (EEG) activity, alongside improvements in stress, anxiety, and mood [4,6-8]. However, findings across psychological outcomes are heterogeneous, and methodological variation in intervention design, outcome measurement, and reporting practices limits cross-study comparability and cumulative synthesis.

Prior Systematic Reviews and Rationale for This Study

Several systematic reviews have examined VRbMIs, though each is constrained in scope in ways that limit cumulative synthesis. Ma et al [9] conducted the first narrative systematic review of immersive VR mindfulness training, including 7 studies focused specifically on whether immersion level moderates mindfulness outcomes. While foundational, that review included no meta-analysis and predates the substantial growth in the literature from 2023 onward. Wieczorek et al [4] conducted the first systematic review and evidence mapping of VRbMIs (search to September 2022), documenting consistent psychological and physiological benefits across 22 studies, including improvements in anxiety, mindfulness, affect, and stress, but explicitly did not perform a meta-analysis due to high methodological heterogeneity across studies. Milasi et al [10] reviewed 16 randomized controlled trials in nonclinical populations only, excluding the clinical, occupational, and mixed methods designs that characterize much of the recent literature. Xie et al [11] conducted a meta-analysis of 25 studies focused specifically on mindfulness as an outcome, without synthesizing the broader psychological profile of VRbMI effects across multiple outcome domains.

No completed review has synthesized empirical studies published between 2023 and 2025, incorporated psychological outcomes across diverse study designs, or evaluated methodological quality using the Mixed Methods Appraisal Tool (MMAT). This review addresses these gaps directly. By extending the search window to April 2025 and including quantitative, quasi-experimental, and mixed methods designs, this study provides an updated and more comprehensive assessment of the VRbMI evidence base than prior reviews have offered.

Literature Context

MBIs have demonstrated benefits for psychological well-being, including reductions in stress, anxiety, and negative affect, across clinical and nonclinical populations [1-3]. As immersive technologies have matured, VR has emerged as a delivery modality for mindfulness practices that integrates guided contemplative instruction, such as breath awareness or body-focused attention, with immersive 3D or 360° environments [4]. VRbMIs typically combine standardized mindfulness guidance with simulated natural or restorative settings, enabling controlled, multisensory delivery of practice within laboratory, clinical, and applied contexts [4]. Empirical studies have shown that brief and multisession VR mindfulness exposures can reduce self-reported stress, anxiety, and negative affect, while also producing physiological indicators associated with relaxation, including changes in heart rate (HR) and HRV [4,6-8]. However, effect magnitudes vary substantially across studies, reflecting differences in intervention duration, guidance style, population characteristics, and the measurement of outcomes. These variations complicate direct comparison across trials and limit conclusions about the consistency and durability of effects.

Wieczorek et al [4] conducted the first systematic review and evidence mapping of VRbMIs, documenting psychological benefits across 22 studies, including improvements in anxiety, mindfulness, affect, and stress—alongside smaller, less consistently reported physiological effects. Notably, the authors explicitly declined to perform meta-analytic pooling due to high methodological heterogeneity across included studies. That review identified several methodological constraints, including small sample sizes, heterogeneity in intervention formats, and limited standardization in physiological reporting [4]. Notably, the review concluded before the publication of a substantial wave of studies between 2023 and 2025. More recent investigations have expanded the evidence base through the inclusion of multisession protocols, active control conditions, and improved VR hardware fidelity, reflecting maturation in both study design and implementation [5-8,10].

Across the emerging literature, researchers have applied VRbMIs in health care, educational, and occupational settings, most commonly targeting anxiety, depression, stress, affective state, and self-reported mindfulness. Physiological end points have included HRV, electrodermal activity, EEG, and cortisol measures, intended to complement subjective outcomes [4]. Despite this breadth, methodological variability remains high. Many studies rely on single-session exposures, convenience samples, or passive control conditions, while others differ in intervention dose and sensory complexity. This diversity contributes to heterogeneity in reported effects and limits the aggregation of cross-study results.

Measurement practices further constrain comparability. Researchers most often assess psychological outcomes using symptom-focused self-report instruments such as the Depression Anxiety Stress Scales, the State-Trait Anxiety Inventory, and the Positive and Negative Affect Schedule. These measures emphasize changes in distress and affective state, reflecting dominant operationalizations used in intervention research. Physiological outcomes, by contrast, are frequently reported incompletely, with missing descriptive statistics or inconsistent baselines that preclude quantitative synthesis [4]. Greater consistency in outcome selection and reporting is therefore necessary to support cumulative evaluation of VRbMIs.

To address these limitations, this meta-analysis integrates findings from the most recent wave of empirical VRbMI research, using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 reporting standards and random-effects procedures that are suitable for heterogeneous, small-sample literatures [12]. The review evaluates methodological quality using the MMAT [13] and quantifies between-study heterogeneity. By updating the cumulative evidence base, this analysis clarifies the strength and consistency of VRbMI effects and identifies methodological priorities for future digital mindfulness research.

Methods

Study Design

A systematic review and quantitative meta-analysis of empirical studies was conducted to examine VRbMIs. We followed the PRISMA 2020 guidelines [12] and applied methodological standards appropriate for small-sample random-effects modeling [12,14].

Eligibility Criteria

We included peer-reviewed empirical studies that evaluated VRbMIs in human participants. Eligible studies implemented a mindfulness-based practice delivered through immersive VR technology (eg, head-mounted displays presenting 3D or 360° environments) and reported at least 1 psychological or physiological outcome relevant to stress, affect, or well-being. We required studies to provide sufficient quantitative data to permit the calculation of effect sizes. To ensure consistent application of inclusion criteria, a mindfulness centrality rubric was developed and applied during full-text screening to evaluate whether each study's intervention met threshold criteria for a recognized mindfulness-based practice. The mindfulness centrality rubric is provided in Multimedia Appendix 1.

While qualitative methods offer valuable insights into the subjective and phenomenological dimensions of mindfulness practice, including participants' lived experience of presence, immersion, and contemplative engagement, the primary aim of this review was to quantify effect sizes across standardized psychological and physiological outcomes to enable meta-analytic pooling. Qualitative data do not permit the calculation of standardized mean differences or the estimation of between-study heterogeneity that meta-analysis requires. This decision necessarily limits the review's capacity to capture experiential dimensions of VRbMIs that may not be adequately represented by symptom-focused instruments. A complementary qualitative synthesis or mixed methods review remains an important direction for future research.

This study encompasses randomized controlled trials, nonrandomized controlled studies, and pre- and postintervention designs to reflect the methodological diversity of the emerging VRbMI literature. Qualitative-only studies, theoretical papers, reviews, protocols, conference abstracts, and dissertations without peer-reviewed publication were excluded. Nonimmersive digital interventions (eg, mobile or desktop mindfulness programs without VR), studies that did not involve a mindfulness-based practice, and studies lacking adequate reporting of outcomes were also excluded, and we limited inclusion to studies involving adult participants (aged 18 years and older), published in English.

Search Strategy

A comprehensive search was conducted across 5 databases: PubMed, PsycINFO, Semantic Scholar, CORE, and Scopus—covering the period from January 2023 to April 2025. The Boolean framework used for all databases was:

- ("mindfulness-based intervention" OR "MBSR" OR "MBCT")
- AND ("virtual reality" OR "VR" OR "immersive virtual reality")
- AND ("stress" OR "anxiety" OR "depression" OR "HRV" OR "EEG" OR "cortisol")

We manually searched reference lists of included studies and prior reviews (eg, Wieczorek et al [4]) to identify additional relevant publications and removed duplicates before screening.

Screening and Study Selection

We screened titles and abstracts for relevance using predefined inclusion criteria and screened full text independently, applying the same criteria to confirm eligibility. A PRISMA 2020 flow diagram summarizes the number of records identified, screened, excluded, and included in the final synthesis. The author (SAB) represents the single screener, having performed the title, abstract, and full-text screening independently using predefined inclusion criteria. Artificial intelligence (AI)–assisted tools (Rayyan, SciSpace, and large language models) were used to support record organization and retrieval; however, we made all inclusion and exclusion decisions.

Of the 2943 records initially retrieved, 45 duplicates were removed, yielding 2898 unique titles and abstracts for screening. At the title and abstract stage, 2764 records were excluded. The most common reasons for exclusion were that the study did not use immersive VR technology, the study did not deliver a structured MBI, the publication type was ineligible (eg, review paper, editorial, theoretical piece, or protocol), or the study lacked sufficient data for synthesis. In cases where abstracts were unavailable, exclusion at this stage was limited to titles that clearly indicated misalignment with inclusion criteria. Of the 134 full-text papers assessed for eligibility, 99 were excluded using a structured tagging system within Rayyan. Exclusion reasons included mindfulness was peripheral or undefined within the intervention (excluded—score 1 peripheral), the study did not use immersive VR (excluded—not VR), the study lacked a structured MBI component (excluded—not MBI), or the full text was inaccessible due to paywall restrictions. A complete record of exclusion tags is available in the Open Science Framework (OSF) repository.

Data Extraction

For each eligible study, data were extracted into a standardized spreadsheet, including authors, publication year, and country; study design and sample size; participant characteristics (age and population type); intervention characteristics (duration, frequency, headset type, environment description, and guidance mode); comparator type; psychological and physiological outcome measures; and pre- and postintervention means, SDs, and sample sizes. When statistics (eg, SDs) were missing, we estimated them from other reported values (eg, 2-tailed t statistics or η^2) using formulas recommended in the Cochrane Handbook for Systematic Reviews of Interventions [15]. Additional variables extracted included participant characteristics, intervention features, and outcome measures. When data were missing or unclear, we applied conservative assumptions and standard estimation procedures and documented them during extraction. All extracted values were double-checked for accuracy. For each outcome domain, all

reported results that permitted effect size calculation were extracted. When multiple measures or time points were reported within a study, we chose the most comparable pre-post or between-group results aligned with the primary analysis. In cases where studies reported results narratively as statistically significant without sufficient statistics for direct calculation, we applied a conservative estimate of g=0.5; for marginal or nonsignificant outcomes, we used g=0.30, following the precedent established by Borenstein et al [16]. Studies for which effect sizes could not be calculated or estimated were excluded from the quantitative synthesis and reported narratively.

Data Preparation and Effect Size Computation

Following data extraction, all variables were organized with the explicit aim of computing standardized mean differences (Hedges g) for psychological outcomes across studies. Extracted data included pre- and postintervention means, SDs, and sample sizes for both within-subject and between-group designs, where available. When studies did not report sufficient statistical detail for direct calculation, consistent estimation procedures were applied to enable inclusion in the quantitative synthesis. We derived SDs from reported SEs or CIs using established formulas (SD=SE × $\sqrt{n}$; SD=[upper CI−lower CI]/[2×t_{crit}]). For within-subject designs lacking a reported pre- and postcorrelation, a conservative estimate of r=0.50 was applied, consistent with recommendations for meta-analytic practice [15,17].

In cases where only test statistics or P values were reported, effect sizes were calculated using established transformation procedures [15,17]. When studies reported outcomes narratively without sufficient statistical detail, conservative estimates were assigned (g=0.50 for statistically significant effects; g=0.30 for marginal or nonsignificant findings), following precedent in prior meta-analytic work [4]. For outcome measures in which higher scores indicated greater symptom severity, effect sizes were reverse-coded so that positive values consistently reflected improvement. When multiple instruments assessed the same construct within a study, we selected the most used measure across the dataset to maintain comparability. All effect sizes were calculated as Hedges g with corresponding SEs and variances, which were subsequently used in random-effects meta-analytic models [14,18,19]. All pooled effects were evaluated using 2-tailed tests (α=.05). We used random-effects models to account for between-study variability.

Risk-of-Bias Assessment

The methodological quality was evaluated using the MMAT 2018 [13]. Certainty of evidence was assessed qualitatively based on study quality (MMAT ratings), consistency of findings, and the extent of between-study heterogeneity. We rated each study across 5 domains: sampling, measurement, confounding, data completeness, and analysis. The ratings were summarized as low, moderate, or high risk of bias. When discrepancies arose during coding, we resolved them by verifying the source texts. Risk-of-bias assessments were conducted by a single reviewer (SAB) using the MMAT 2018 criteria. All ratings were performed independently, with AI-assisted tools used only to support identification of methodological details and not to determine final judgments.

Effect-Size Calculation and Data Synthesis

We computed effect sizes for continuous outcomes as standardized mean differences (Hedges g) with corresponding SEs and 95% CIs. For within-subject designs, we assumed a conservative pre- and postcorrelation of r=0.50 when studies did not report this value. Random-effects models were used for all pooled analyses to account for expected between-study heterogeneity, estimating between-study variance with the DerSimonian-Laird method [14]. Although DerSimonian-Laird estimation is standard in small-sample meta-analyses, it may underestimate uncertainty under conditions of extreme heterogeneity; results should therefore be interpreted conservatively [14]. We included studies in the quantitative synthesis when sufficient statistical data were available to compute effect sizes. We retained studies that met the inclusion criteria but did not report adequate data for narrative synthesis and prepared data for synthesis by converting reported statistics into standardized mean differences (Hedges g). When summary statistics were incomplete, conservative estimation procedures were applied to derive effect sizes.

Outcome Classification

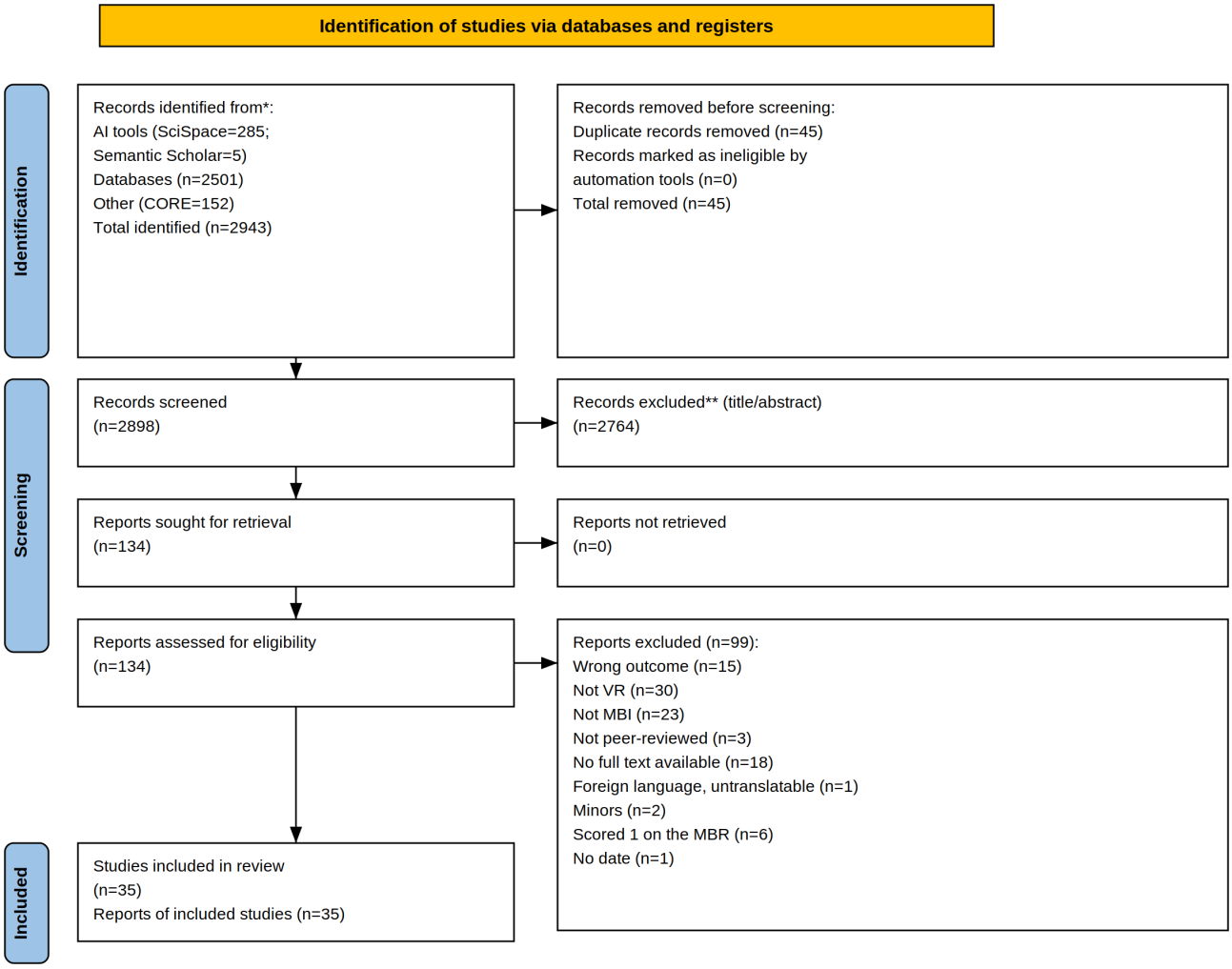
We selected the 6 primary psychological outcome domains synthesized in this review—anxiety, depression, stress, negative affect, positive affect, and mindfulness—a priori based on 2 converging rationales. First, these domains were retained from Wieczorek et al [4] to ensure methodological continuity and enable direct comparison with the prior evidence base [4]. Second, they represent the outcome categories most consistently reported across the VRbMI literature, as identified during preliminary screening. Stress, anxiety, and depression reflect the dominant clinical targets of MBIs in Western psychological research [2,4]; positive and negative affect capture the broader affective profile of intervention response [4]; and mindfulness—assessed as both state and trait—directly indexes the contemplative construct central to all included interventions [1,2]. Domains such as sleep, cognition, and pain were reported by a subset of studies but were insufficiently represented across the sample to support meta-analytic pooling and were therefore retained for narrative description only. The distribution of outcome domains across the 35 included studies was as follows: anxiety (n=17, 49%), depression (n=17, 49%), stress (n=10, 29%), mindfulness (n=18, 51%), negative affect (n=4, 11%), and positive affect (n=4, 11%).

Results

Study Selection

Following the PRISMA 2020 reporting guidelines, study identification, screening, and inclusion were documented using a transparent flow diagram [12]. The search identified 2943 records from bibliographic databases and AI-assisted retrieval tools. After removing duplicates, we screened 2898 unique titles and abstracts and assessed 134 full-text papers for eligibility. Of these, 35 studies met all inclusion criteria and were included in the final synthesis. Figure 1 presents the PRISMA flow diagram summarizing the screening process and study selection. The completed PRISMA 2020 checklist is provided in Checklist 1.

Figure 1. PRISMA 2020 flow diagram of study selection. The diagram depicts the number of records identified, screened, excluded, and retained in the final synthesis. *Records identified using AI-assisted tools (SciSpace, Semantic Scholar) and traditional databases. **Reasons for exclusion at the title/abstract stage were not individually categorized; the total reflects records not meeting VR-MBI criteria, empirical study requirements, or relevance thresholds. AI: artificial intelligence; MBI: mindfulness-based intervention; MBR: mindfulness centrality rubric; PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses; VR: virtual reality.



Study Characteristics

The 35 included studies encompassed a range of quantitative and mixed methods designs, including randomized controlled trials, quasi-experimental studies, and nonrandomized formats. The studies examined clinical, educational, and occupational populations, including individuals with depression, anxiety disorders, or psychosis [20,21], health care professionals experiencing burnout [22,23], patients with cancer [24,25], and university students engaged in mindfulness-based training [6,26,27]. McConnell et al [28] examined VR mindfulness for chronic low back pain in a 2-arm randomized trial, measuring disability and pain intensity across 12 sessions. Torres García et al [29] examined emotional discomfort in patients with breast cancer using the Emotional Discomfort Detection scale prior to first chemotherapy; while the VR group showed improvement trends, statistical reporting was insufficient for effect size computation, and the study was retained for narrative description only.

Geographically, the evidence base spanned North America, East Asia, and Europe, reflecting the growing international interest in VRbMIs. Studies were conducted in the United States [22,25,30-33], China [6,24,34], Taiwan [7], Finland [35], Spain [5,26,36], the United Kingdom [37], South Korea [21,38,39], and Turkey [40]. Supplementary visual summaries of study characteristics, including demographic figures and geographic distribution, are available in the OSF repository. Table 1 presents detailed characteristics of all included studies, including study design, population, intervention features, and outcome measures, in accordance with PRISMA 2020 reporting standards.

Table . Characteristics of included studies (N=35).

Study	Design	Values, n	Population	Intervention (dose)	Model	Guide	Comparator	Outcomes	Time	MMAT[a]	*g*
Ch et al (2023) [13]	Experiment	20	Remote workers	VR[b] mindfulness (9 weeks)	360° video	Mixed	Control	Stress, creativity	Pre or post	Low-moderate	−0.57
Barton et al (2024) [35]	Mixed	58	Adults	VR mindfulness (1×6 minutes)	Mixed or multimodal	Guided	VR conditions	Mindfulness, fatigue, mood	Pre or post	Moderate	1.22
Blackmore et al (2024) [20]	Mixed	27	Clinical	VR mindfulness (1×15 minutes)	360° video	Guided	None	Anxiety, mood, mindfulness	Pre or post	Moderate	1.26
Cano et al (2024) [5]	Quasi-experiment	31	Post-COVID-19	VR mindfulness (16×60 minutes)	CAVE[c]	Guided	None	Cognition, attention	Pre or post	High	0.01
Cawley and Tejeiro (2024) [27]	Quasi-experiment	67	Students	VR mindfulness (1×10 minutes)	360° video	Guided	Audio, coloring	Stress, well-being	Pre or post	Low-moderate	0.34
Chen et al (2024) [41]	RCT[d]	76	Adults	VR mindfulness (8×18 minutes)	App-based VR	Guided	Control	Anxiety, depression	Pre or post+FU	Low	0.99
Ferrer Costa et al (2024) [23]	Pilot	83	Health care workers	VR mindfulness (8×13 minutes)	Immersive VR	Guided	None	Burnout, engagement	Pre or post	Low-moderate	−0.56
Fonseca et al (2024) [31]	RCT	26	Caregivers	VR mindfulness (1×6 minutes)	Immersive VR	Guided	Control	Anxiety	Pre or post	Moderate	−0.75
Franklin et al (2023) [25]	RCT	36	Patients with cancer	VR mindfulness (1×10 minutes)	Immersive VR	Guided	Control	Anxiety, depression	Pre or post	Low	NR[e]
Garland et al (2024) [32]	Pilot	34	SUD[f]	VR mindfulness (8×15 minutes)	App-based VR	Guided	None	Craving, mood	Pre or post	Low	0.53
Han et al (2023) [39]	Experiment	40	Students	VR meditation (1×10 minutes)	Immersive VR	Guided	Control	Anxiety	Pre or post	Moderate	N/A[g]
Hanna et al (2025) [37]	Quasi-experiment	32	Students	VR mindfulness (4 - 8 weeks)	Immersive VR	Guided	No VR	Mindfulness	Pre or post	Moderate	N/A

Study	Design	Values, n	Population	Intervention (dose)	Model	Guide	Comparator	Outcomes	Time	MMAT[a]	*g*
Jimenez-Barragan et al (2025) [36]	RCT	70	Pregnant women	VR mindfulness (6 weeks, daily 14 minutes)	Immersive VR	Guided	Standard care	Pain, anxiety	Pre or post	Moderate	3.92
Kamada et al (2025) [42]	RCT	10	Patients undergoing surgery	VR mindfulness (NR[e])	Immersive VR	Guided	Standard care	Pain, anxiety	Pre or post	Moderate	−1.49
Kim et al (2024) [38]	Experiment	8	Dementia	VR mindfulness (6 sessions)	Immersive VR	Guided	None	Anxiety, depression	Pre or post	Lo	N/A
Kim et al (2024) [43]	Experiment	60	Students	VR meditation (5×30 minutes)	360° video	Guided	Control	Sleep, HRV[h]	Pre or post	Low	1.28
Kumar et al (2024) [44]	RCT	40	Students	VR meditation (3×10 minutes)	Immersive VR	Guided	Control	EEG[i], stress	Pre or post	Low-moderate	1.33
Lee et al (2023) [21]	RCT	64	Psychosis	VR mindfulness (8×30 minutes)	Mixed or multimodal	Guided	Control	Symptoms	Pre or post	Moderate	0.52
Liu et al (2025) [34]	RCT	90	Postpartum	VR mindfulness (8 weeks)	Immersive VR	Guided	Control	Anxiety, depression	Pre or post+FU[j]	Moderate	0.83
Mancini et al (2024) [45]	Experiment	21	Adults	VR mindfulness (NR)	Interactive	Guided	Audio	Mindfulness	Pre or post	Moderate	N/A
Mao et al (2024) [24]	Experiment	48	Patients with cancer	VR mindfulness (4×60 minutes)	360° video	Guided	None	Anxiety, fatigue	Pre or post+FU	Low-Moderate	1.93
Mc-Connell et al (2024) [28]	RCT	52	Chronic pain	VR mindfulness (12	Mixed or multimodal	Guided	Standard care	Pain, disability	Pre or post	High	1.33
Modrego-Alarcón et al (2025) [26]	RCT	93	Students	VR mindfulness (6×7.5 minutes)	Immersive VR	Guided	Control	Mindfulness	Pre or post	Low	1.73
Murray et al (2024) [46]	Mixed	38	TBI[k]	VR mindfulness (4-minute sessions)	Immersive VR	Guided	None	Distress	Pre or post	Low	0.68
Ng et al (2024) [7]	Experiment	51	Students	VR breathing (4×6 minutes)	Immersive VR	Mixed	Control	EEG	Pre or post	Moderate	N/A

Study	Design	Values, n	Population	Intervention (dose)	Model	Guide	Comparator	Outcomes	Time	MMAT[a]	*g*
Olasz et al (2024) [8]	RCT	56	Students	VR mindfulness (2×20 minutes)	Immersive VR	Guided	Tablet	Anxiety, HR[l]	Pre or post	Moderate	1.07
Ong et al (2025) [47]	Mixed	35	Educators	VR mindfulness (1×10 minutes)	360° video	Guided	None	Mindfulness, UX[m]	Pre or post	Low	N/A
Poetar et al (2023) [48]	RCT	47	Adults	VR mindfulness (1×30 minutes)	App-based VR	Guided	Desktop	Mood	Pre or post	Moderate-high	0.58
Sexton-Radek et al (2024) [49]	Mixed	3	Students	VR mindfulness (7×15 minutes)	Immersive VR	Guided	None	Sleep	Pre or post	High	N/A
Sezer et al (2025) [40]	Experiment	54	Adults	VR mindfulness (1×20 minutes)	Immersive VR	Guided	Control	Anxiety, HRV	Pre or post	Moderate	0.50
Spitz et al (2024) [33]	Pilot	27	Dysphoria	VR mindfulness (2 weeks)	Immersive VR	Guided	None	Mood	Pre or post	Moderate	N/A
Torres García et al (2024) [29]	Quantitative (NR)	NR	Adults	VR mindfulness (NR)	Immersive VR	Guided	None	Emotional discomfort	Pre or post	High	N/A
Van Doren et al (2024) [30]	Mixed	32	Veterans	VR mindfulness (1×60 minutes)	360° video	Guided	None	Mindfulness	Pre or post	Moderate	−0.98
Williams et al (2024) [22]	Experiment	61	Health care workers	VR mindfulness (5 - 15 minutes)	Immersive VR	Guided	None	Stress, engagement	Pre or post	Moderate	1.01
Zheng et al (2024) [6]	RCT	60	Students	VR mindfulness (2 weeks)	Immersive VR	Guided	Control	Anxiety, depression	Pre or post+FU	Low	1.81

[a]MMAT: Mixed Methods Appraisal Tool.

[b]VR: virtual reality.

[c]CAVE: room-scale CAVE system.

[d]RCT: randomized controlled trial.

[e]NR: not reported. Effect size could not be calculated due to the absence of a control or comparator group.

[f]SUD: substance use disorder.

[g] N/A: not available; effect size could not be calculated; study reported only *P* values and percentage change without group-level means and SDs necessary to compute Hedges *g*.

[h]HRV: heart rate variability.

[i]EEG: electroencephalography.

[j]FU: follow-up.

[k]TBI: traumatic brain injury.

[l]HR: heart rate.

[m]UX: user experience.

Risk of Bias Assessment

Using the MMAT [13], we evaluated the methodological quality of all 35 included studies across 5 domains: sampling, measurement, confounding, data completeness, and analysis. Overall, most studies were rated as having a moderate risk of bias (n=22), reflecting partial adherence to quality criteria, commonly due to limited reporting of randomization procedures, incomplete follow-up data, or small sample sizes. In total, 11 studies met most or all MMAT criteria and were rated low risk. In contrast, we rated 3 studies as high risk due to inadequate control of confounding variables or incomplete reporting of outcomes. Among randomized controlled trials, methodological quality was generally strong, with clear descriptions of participant allocation and intervention fidelity. However, many trials did not report whether outcome assessors were blinded, and adherence monitoring was often limited. Nonrandomized designs exhibited a higher risk of bias in sampling and confounding domains, primarily due to convenience recruitment and the absence of active control conditions. Mixed methods studies demonstrated a moderate to high risk of bias, primarily due to the limited integration between the qualitative and quantitative components.

AI-assisted tools supported this appraisal by facilitating the identification of relevant methodological details within full-text papers; we reviewed all AI-assisted outputs before assigning final MMAT ratings. Table 2 summarizes the distribution of risk-of-bias ratings by study design.

Table . Risk of bias summary of study design.

Domain and score (low, moderate, or high)	Count, n
Quantitative randomized controlled trial	
High risk	1
Moderate risk	5
Low risk	8
Quantitative nonrandomized	
High risk	1
Moderate risk	13
Low risk	0
Quantitative nonrandomized or mixed methods	
High risk	1
Moderate risk	4
Low risk	2

Quantitative Results

Overview

Following the risk-of-bias appraisal, quantitative outcomes were synthesized across the 35 included studies using standardized mean difference estimates. We conducted analyses using random-effects models to account for between-study variability and expressed all effect sizes as Hedges *g*, along with corresponding 95% CIs. The random-effects weighting was applied to minimize bias from unequal sample sizes and heterogeneous designs. When studies did not report complete statistics (eg, pre-post means, SDs, or sample sizes), we applied conservative estimation rules based on the direction and significance of reported effects, following Hedges [15] and guidelines for small-sample meta-analyses. All statistical transformations and pooling procedures were performed in JASP (version 0.19; University of Amsterdam) using the DerSimonian-Laird estimator for between-study variance [14], consistent with Hedges [15] framework and contemporary guidelines for small-sample meta-analyses [18].

The quantitative synthesis focused on 6 primary psychological outcome domains reported across multiple studies: anxiety, depression, stress, negative affect, positive affect, and mindfulness. Each outcome is summarized below, with pooled effect sizes, CIs, and heterogeneity statistics. Forest plots for all meta-analytic models, including study-level and pooled estimates, are available in the project's OSF repository. The following sections present each outcome domain sequentially, beginning with anxiety, the most frequently reported psychological variable in the included studies. Studies contributing to each synthesis varied in design, sample characteristics, and risk of bias, with most rated low to moderate quality using MMAT criteria.

Anxiety

In total, 27 effect size estimates from 13 studies provided sufficient data for meta-analysis. A random-effects model indicated a small-to-moderate, nonsignificant pooled effect on anxiety (g=0.44, 95% CI –0.08 to 0.96; t_{26}=1.74; P=.09). Between-study heterogeneity was substantial (Q_{26}=381.60; P<.001; τ^2=0.96), reflecting considerable variability in intervention design, population characteristics, and outcome measurement [15-17].

Depression

In total, 10 studies yielding 18 effect size estimates provided sufficient statistical data for meta-analysis. A random-effects

model yielded a moderate pooled effect (g=0.62, 95% CI –0.13 to 1.36]; t_{17}=1.75; P=.10); however, the CI crossed 0, indicating that the effect was not statistically significant. Between-study heterogeneity was substantial (Q_{17}=236.77; P<.001; τ^2=1.09) [15-17].

Stress

In total, 6 studies yielding 10 effect size estimates reported stress-related outcomes using validated self-report instruments, including the Perceived Stress Scale, the Depression, Anxiety and Stress Scale-21 stress subscale, or comparable measures [6,13,22,27,44,46]. Participant populations included university students, health care professionals, and community adults across both single-session and multiweek interventions. Individual study effect sizes varied across intervention formats. Some studies reported large reductions in perceived stress following immersive MBIs (eg, Kumar et al [44], g=1.33; Zheng et al [6], g=1.81), whereas others reported moderate or small effects following brief or lower-intensity interventions (eg, Murray and Shmidheiser [46], g=0.68; Cawley and Tejeiro [27], g=0.34). In occupational samples, effects were small or negligible [22]. A random-effects meta-analysis yielded a small-to-moderate pooled effect that did not reach statistical significance (g=0.45, 95% CI −0.08 to 0.99; t_9=1.90; P=.09). Between-study heterogeneity was substantial (Q_9=54.26; P<.001; τ^2=0.35) [15-17].

Negative Affect

In total, 3 studies yielding 4 effect size estimates reported changes in negative affect using validated self-report instruments, including the Positive and Negative Affect Schedule (PANAS) and the Profile of Mood States [20,30,48]. Participant samples included university students, individuals enrolled in recovery programs, and nonclinical adult populations. Across studies, individual effect sizes indicated reductions in negative affect following MBIs delivered in VR and non-VR formats. Van Doren et al [30] reported a large pre- and postreduction following a brief immersive VR mindfulness session (g=–0.98), whereas Blackmore et al [20] observed a moderate reduction following a VR-supported mindfulness practice emphasizing curiosity and decentering (g=–0.60). Poetar et al [48] reported similar decreases in negative affect in both VR-based (g=–0.58) and desktop-based (g=–0.68) mindfulness conditions. A random-effects meta-analysis yielded a large and statistically significant pooled effect on negative affect (g=–0.67, 95% CI –0.92 to −0.42; t_3=–8.71; P=.003). Between-study heterogeneity was negligible (Q_3=0.93; P=.82; τ^2=0.00) [15-17].

Positive Affect

In total, 3 studies yielding 4 effect size estimates assessed positive affect outcomes using the PANAS or comparable mood indices [20,30,48]. Participant samples included university students, clinical groups, and general adult populations. Individual study findings were variable. Van Doren et al [30] reported a moderate increase in positive affect following a single immersive mindfulness session (g=0.80). Poetar et al [48] reported a slight increase in the VR condition (g=0.27) and a slight decrease in the desktop-based comparison condition (g=–0.31). Blackmore et al [20] observed a slight, nonsignificant increase in positive affect (g=0.28). A random-effects meta-analysis yielded a small, pooled effect that did not reach statistical significance (g=0.24, 95% CI –0.45 to 0.92; t_3=1.10; P=.35). Between-study heterogeneity was modest (Q_3=6.58; P=.09; τ^2=0.09) [15-17].

Mindfulness

In total, 18 studies assessed mindfulness-related outcomes using validated self-report instruments, including the State Mindfulness Scale, Five Facet Mindfulness Questionnaire, and Toronto Mindfulness Scale [20,26,27,30,35,37,45,47]. These measures captured both state and trait aspects of mindfulness following exposure to VRbMIs. Individual study findings varied across intervention formats and outcome measures. Cawley and Tejeiro [27] reported significant gains in state mindfulness following a brief VR session (d=0.69), whereas Blackmore et al [20] observed large pre- and posteffects for curiosity (g=1.26) and decentering (g=1.51). Modrego-Alarcón et al [26] reported smaller but measurable effects across multiple VR environments. Other studies reported modest changes following repeated exposure protocols.

In total, 2 studies yielding 5 effect size estimates using the State Mindfulness Scale provided sufficient data for quantitative synthesis. A random-effects meta-analysis yielded a large, statistically significant pooled effect on state mindfulness (g=1.00, 95% CI 0.32-1.68; t_4=4.11; P=.02). Between-study heterogeneity was moderate (Q_4=12.37; P=.02; τ^2=0.21), reflecting variability in VR environment type and delivery format across conditions [15-17].

Physiological Outcomes

Several studies included physiological measures alongside psychological outcomes; however, reporting was inconsistent and often incomplete. Standard indices included HR, HRV, electrodermal activity (or skin conductance level), EEG, and cortisol. Because most studies did not report sufficient statistics for quantitative pooling, physiological outcomes were summarized descriptively. Across studies, reported physiological changes generally corresponded with reductions in autonomic arousal following VR-based mindfulness exposure. Kim et al [38] reported increased HRV and reduced HR during guided VR meditation compared with a neutral VR control condition. Ng et al [7] observed decreased skin conductance levels and increased alpha EEG activity during mindfulness-based VR sessions. Williams et al [22] documented reductions in HR and respiration rate among health care professionals during immersive breath-awareness practice. Kamada et al [42] evaluated immersive VR for reducing intraoperative pain and anxiety in patients undergoing surgery in a single-center pilot randomized controlled trial conducted in Helsinki. Sexton-Radek et al [49] measured salivary melatonin, subjective calm, and sleep efficiency in a small mixed methods study, with participants reporting greater relaxation and modest improvements in sleep scores over 5 days; however, no statistical testing was conducted.

Only 5 studies provided analyzable physiological statistics, and baseline definitions varied substantially across designs. As a result, we did not conduct a formal meta-analysis of physiological outcomes. Heterogeneity in study design, small sample sizes, and variability in outcome reporting limited overall confidence in the evidence. Findings for stress-related outcomes supported greater confidence, while substantial heterogeneity across anxiety studies reduced confidence in those pooled estimates.

Discussion

Overview

This review synthesized evidence from 35 empirical studies examining VRbMIs to evaluate psychological outcomes and methodological quality. Across studies, VRbMIs were associated with favorable short-term psychological outcomes, most notably a large, significant reduction in negative affect and a large, significant increase in state mindfulness, alongside nonsignificant trends toward improvement in stress, anxiety, and depression. Pooled effect sizes ranged from small to moderate (g=0.24 - 0.45) for affect, stress, anxiety, and depression outcomes, and large for negative affect (g=–0.67) and state mindfulness (g=1.00). Physiological outcomes, including changes in HR, HRV, and electroencephalographic markers, generally aligned with self-reported psychological findings; however, inconsistent and incomplete reporting precluded a quantitative synthesis. Taken together, the evidence suggests that VRbMIs can function as short-term supports for emotion regulation and attentional training. Although several pooled effects did not reach statistical significance, the overall direction and consistency of findings across studies, particularly for stress-related outcomes, support a cautious interpretation of short-term benefit. At the same time, these findings highlight methodological constraints that continue to shape how mindfulness is operationalized and evaluated within this emerging body of research.

Psychological and Physiological Findings

Across diverse populations, including students, health care professionals, and clinical groups, VRbMIs showed directionally consistent improvements in stress, anxiety, and depressive symptoms, though pooled effects for these outcomes did not reach statistical significance consistent with the direction of prior meta-analytic findings [4]. Effects were generally larger in interventions that combined immersive environments with explicit mindfulness instruction or interactive guidance [6,20]. In contrast, outcomes related to positive affect and trait mindfulness were smaller and less consistent, suggesting that VRbMIs primarily support short-term emotional regulation rather than stable dispositional change. Most studies operationalized mindfulness using standardized psychological instruments such as the Depression, Anxiety and Stress Scale-21 (DASS-21), State-Trait Anxiety Inventory, and PANAS. While these measures facilitate cross-study comparability, they predominantly frame mindfulness in terms of symptom reduction and self-regulation. The inclusion rubric applied in this review excluded VR applications that focused solely on relaxation or entertainment, ensuring conceptual alignment with mindfulness-based practice.

Nevertheless, the resulting evidence base largely reflects a biomedical orientation that emphasizes stress management over broader contemplative dimensions. Of the 35 included studies, stress, anxiety, and depression were the 3 most frequently measured outcomes, while positive affect and mindfulness trait measures appeared in fewer than half of the studies, and no included study explicitly measured contemplative outcomes such as compassion, equanimity, insight, or nonattachment. This pattern mirrors broader critiques of secular mindfulness research, which has been characterized as prioritizing symptom reduction and clinical utility over the cultivation of wisdom, ethical development, and the liberative dimensions central to traditional Buddhist practice [3,50,51]. The dominance of distress-focused outcome measures reflects the influence of Western psychological frameworks, particularly cognitive-behavioral models on how mindfulness is operationalized and evaluated in digital health research.

Compared with Wieczorek et al [4], the present synthesis incorporates a broader and more methodologically diverse set of studies, including recent randomized trials and multisession interventions. While overall effect patterns remain broadly consistent, the inclusion of newer studies increases heterogeneity and reduces confidence in pooled estimates for several outcomes, particularly anxiety and mindfulness. These findings suggest that earlier estimates may have reflected smaller, more homogeneous samples.

Methodological and AI Contributions

Despite rapid growth in VRbMI research between 2023 and 2025, methodological rigor across studies remained uneven. Common limitations included small sample sizes, brief intervention durations, limited follow-up, and reliance on single-group pre- and postdesigns. These features constrained statistical power and reduced confidence in causal inference. Even among randomized controlled trials, control conditions often failed to match VR interventions in terms of duration, engagement, or sensory load, complicating the interpretation of intervention-specific effects. Heterogeneity in outcome measures, intervention protocols, and reporting formats further limited comparability across studies. The methodological and epistemic dimensions of the AI-assisted review process used in this study are examined in depth in a companion paper currently under review.

Conceptual Implications for Measurement and Design

Beyond procedural improvements, this review highlights a broader conceptual pattern in how mindfulness is represented within VR research. Nearly all included studies framed mindfulness as a culturally neutral attentional or stress-reduction technique, operationalized through symptom-focused instruments and evaluated against biomedical outcome criteria. While this approach supports cross-study comparability and clinical applicability, it narrows the construct of mindfulness to outcomes measurable within Western psychological paradigms. The epistemological and cultural dimensions of this narrowing, including how AI-assisted retrieval tools may

reproduce dominant publication biases and how outcome measures embed assumptions about selfhood and well-being, are examined in depth in a companion paper currently under review. This analysis focuses on the methodological and empirical implications of these patterns for the design and synthesis of VRbMI research.

Limitations and Future Directions

Several limitations constrain the interpretation of these findings. We did not conduct a sensitivity analysis due to the limited number of studies per outcome and substantial heterogeneity in study design and reporting, which constrained the feasibility of meaningful robustness testing. Many studies relied on small samples, brief follow-up periods, and incomplete statistical reporting, which reduced precision and limited the estimation of effect sizes. Substantial heterogeneity across interventions, outcome measures, and study designs further restricted comparability. Physiological outcomes showed potential value but were rarely reported with sufficient detail to support interpretation or synthesis. We did not conduct analyses to explore sources of heterogeneity (eg, subgroup analysis or meta-regression) due to the limited number of studies per outcome and variability in study designs. Further, we did not assess reporting bias (eg, publication bias) due to the small number of studies per outcome and heterogeneity in study designs.

At the review level, reliance on English-language publications likely introduced selection bias aligned with the dominant biomedical literature [52]. AI-assisted tools supported literature retrieval and screening. A complete methodological and epistemic analysis of this process appears in a separate paper currently under review and is therefore not reproduced here. Although the use of a structured inclusion rubric helped limit conceptual drift, future research should address both methodological and conceptual gaps. Larger trials with active control conditions and clearer reporting standards are necessary to clarify mechanisms and the durability of effects. For physiological measures in particular, a minimal reporting set specifying devices, sampling rates, preprocessing decisions, and measurement windows would enable cross-study comparison and longitudinal analysis. Beyond methodological rigor, future work should expand its conceptual scope by incorporating culturally grounded frameworks and qualitative or phenomenological methods capable of capturing the ethical, relational, and experiential dimensions of practice.

A further limitation concerns the sole-author design of this review. Although sole-authored systematic reviews are not uncommon in emerging fields, they introduce heightened risk of selection bias, confirmatory screening, and inconsistent application of inclusion criteria across a large study set. To mitigate these risks, we applied a structured, prespecified inclusion rubric documented in the PROSPERO registration and available in the OSF repository. We operationalized each criterion as a binary decision rule prior to screening and implemented a structured tagging system within Rayyan to document inclusion and exclusion decisions transparently at each stage. Each record was tagged with a specific reason code (eg, “not immersive VR,” “no mindfulness component,” and “insufficient data”) to ensure consistent and auditable decision-making throughout the screening process. Screenshots of the tagging workflow are available in the OSF repository. In cases where a study’s eligibility remained ambiguous, for example, when a VR application was described as “relaxation-based” but incorporated explicit breath-awareness or body-scan elements, we resolved uncertainty by returning to the primary source, applying the most conservative interpretation of the inclusion criterion, and documenting the decision rationale in the extraction log. Where ambiguity persisted after this process, we excluded the study. This approach prioritized consistency and transparency.

Implications

These findings have implications for practice, research design, and theory. In applied contexts, VRbMIs provide a flexible format for supporting stress and emotion regulation in educational, clinical, and workplace settings. Their value lies less in novelty than in their capacity to scaffold attention and engagement for populations that may struggle with conventional practice formats. For researchers, the synthesis highlights the importance of standardized outcome reporting and transparent documentation of review processes. Without shared reporting conventions, especially for physiological measures, the field limits its ability to build cumulative knowledge. Transparency in both measurement and retrieval practices remains essential for interpretability and reproducibility. At a theoretical level, the review demonstrates that the tools used to study mindfulness also participate in defining it. Aligning intervention design and measurement with contemplative concerns such as attention, care, and interdependence may help balance methodological precision with conceptual integrity. Under these conditions, technological innovation can support the continuity rather than dilute the mindfulness practice.

Conclusions

This synthesis of 35 empirical studies indicates that VRbMIs produce a large, statistically significant reduction in negative affect (g=–0.67; P=.003) and a large, statistically significant increase in state mindfulness (g=1.00; P=.02). Effects on depression (g=0.62; P=.10), stress (g=0.45; P=.09), and anxiety (g=0.44; P=.09) were small to moderate and did not reach statistical significance, though their direction was consistently positive. Effects on positive affect (g=0.24; P=.35) and trait mindfulness were small and less consistent, and physiological outcomes, while directionally aligned with self-reported findings, could not be formally synthesized due to incomplete reporting. Despite substantial heterogeneity across outcomes, the overall pattern of findings supports the use of VR-based mindfulness as a low-risk and accessible intervention across diverse populations. At the same time, the evidence base remains shaped by limited sample sizes, inconsistent physiological reporting, and a dominant biomedical framing that prioritizes symptom reduction over practice context. Future research that integrates rigorous trial design, transparent reporting practices, and culturally situated conceptual frameworks will better support both scientific credibility and theoretical coherence. Such integration may help ensure that VR-based mindfulness research advances not only technical effectiveness but also the broader

purpose of mindfulness as a practice oriented toward awareness, responsibility, and human flourishing.

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Data Availability

The datasets generated and analyzed during this study are openly available in the Open Science Framework repository [53]. These materials include the extracted study data, computed effect sizes (Hedges *g*), analytic outputs, and supporting documentation. All data were derived from previously published studies; no individual participant data were collected or used.

Authors' Contributions

Conceptualization: SAB (lead)
Methodology: SAB
Software: SAB
Formal analysis: SAB
Investigation: SAB
Data curation: SAB
Writing—original draft: SAB
Writing—review and editing: SAB, AJM-N, RMT, AR
Visualization: SAB
Project administration: SAB
Supervision: AJM-N, RMT, AR

Conflicts of Interest

None declared.

Multimedia Appendix 1
Mindfulness centrality rubric: inclusion criteria and screening procedures for virtual reality–based mindfulness interventions.
[PDF File, 169 KB - xr_v3i1e90003_app1.pdf]

Checklist 1
PRISMA checklist.
[DOCX File, 281 KB - xr_v3i1e90003_app2.docx]

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Abbreviations

AI: artificial intelligence
EEG: electroencephalography
HR: heart rate
HRV: heart rate variability
MBI: mindfulness-based intervention
MMAT: Mixed Methods Appraisal Tool
OSF: Open Science Framework
PANAS: Positive and Negative Affect Schedule
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
VR: virtual reality
VRbMI: virtual reality–based mindfulness intervention

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Persuasive Gamified Virtual Reality Experience to Enhance Engagement and Focus in Young Adults With Mild Anxiety Symptoms: Randomized Pilot Experimental Study

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Abstract

Background: Anxiety-related symptoms are prevalent and can negatively affect concentration, motivation, and overall well-being. Traditional treatments such as cognitive behavioral therapy and medication work well for clinical anxiety disorders. However, individuals with anxiety often struggle with access, adherence, and staying engaged in treatment. Emerging technologies such as virtual reality (VR) and gamification offer new opportunities to enhance user engagement and motivational processes within digital mental health applications.

Objective: This study introduces *Cleanify*, a gamified VR cleaning simulation designed using the Octalysis framework and the persuasive system design model. The objective was to evaluate whether gamification elements improve user engagement, focus, and satisfaction compared to a nongamified version among individuals experiencing anxiety symptoms. We hypothesized that the gamified version would outperform the nongamified version in enhancing user engagement, immersion, and overall user experience.

Methods: A pilot experimental study was conducted with 50 participants aged 18 to 39 years recruited from the general population in northern Sweden. Participants were randomly assigned to either a gamified or nongamified version of the *Cleanify* VR application and completed a single 15-minute VR session using the Oculus Quest headset. Baseline anxiety symptoms were assessed using the Generalized Anxiety Disorder–7 scale for descriptive purposes only. Postintervention outcomes included focus and immersion measured using the Flow State Scale and user experience measured using the short version of the User Experience Questionnaire. Group differences were analyzed using 2-tailed independent-sample *t* tests.

Results: Participants using the gamified VR version demonstrated higher engagement and immersion than those using the nongamified version. The gamified group reached higher in-game levels overall, with a greater proportion of participants reaching level 3 (17/25, 68% vs 8/25, 32%), and reported higher recommendation scores (mean 4.20, SD 0.76 vs 3.36, SD 0.86). Significant group differences were observed for overall flow (t_{48}=3.87; P<.001), fluency (t_{48}=4.36; P<.001), and absorption (t_{48}=2.80; P=.008). User Experience Questionnaire results indicated higher pragmatic quality, hedonic quality, and overall user experience in the gamified condition.

Conclusions: Integrating gamification into a VR environment significantly enhanced user engagement, focus, and immersion in this pilot sample. These findings provide preliminary evidence that gamified VR design elements can positively influence user experience outcomes. Further research incorporating longitudinal designs and clinical outcome measures is needed to determine potential relevance.

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KEYWORDS

human-computer interaction; user-centered design; virtual reality; VR; game; gamification; anxiety; disorder; adult; young adults; generalized anxiety disorder; GAD; mental health; randomized; controlled trial; randomized controlled trial; RCT; questionnaire; persuasive technology

Introduction

Mental health conditions such as anxiety and depression affect nearly 1 in 8 people worldwide, with prevalence rising since the COVID-19 pandemic [1,2]. Anxiety-related symptoms, including excessive worry, restlessness, difficulty concentrating, and physical tension, are commonly reported across both clinical and nonclinical populations [3,4]. While treatments such as cognitive behavioral therapy and pharmacological interventions are effective for diagnosed anxiety disorders, many individuals experiencing mild or subclinical anxiety symptoms remain untreated due to stigma, limited access to care, and challenges with treatment adherence [5-7]. Research further indicates that anxiety is associated with difficulties in attentional control and emotional regulation, highlighting the importance of interventions that support focus, engagement, and adaptive coping strategies [8,9].

Virtual reality (VR) has emerged as a promising tool for mental health interventions, offering immersive, controlled environments for practicing mindfulness and exposure therapy [4,10,11]. Compared to traditional approaches, VR can increase motivation and simulate real-world contexts safely [12,13]. Applications such as *SnowWorld* have demonstrated VR's potential in stress and pain reduction, and VR-based exposure therapies have been successfully applied to disorders such as phobias and posttraumatic stress disorder [14-16].

Alongside VR, gamification—the integration of gamelike elements such as points, levels, and rewards—has been shown to improve motivation and sustain engagement in therapeutic contexts [17-19]. Recent studies combining gamification with VR have produced encouraging results for social anxiety, phobias, and public speaking interventions, reporting greater immersion and positive user experiences [20-22].

Building on this work, this study introduces *Cleanify*, a VR house cleaning simulation developed using principles of persuasive system design and gamification. Cleaning activities were chosen because they are familiar, accessible, and low barrier, whereas research indicates that they can reduce stress and restore a sense of control [23,24]. By embedding mindfulness into structured, repetitive cleaning tasks, the intervention offers a practical way to cultivate focused attention.

This early-stage pilot study compared gamified and nongamified versions of *Cleanify* to evaluate their impact on user engagement, immersion, and satisfaction. The research question was as follows: how do users perceive focus, immersion, and engagement in gamified vs nongamified versions of VR mindfulness applications? The findings aim to inform the design and optimization of future VR interventions targeting individuals experiencing mild anxiety symptoms, particularly by enhancing user motivation and sustained participation.

Methods

Theoretical Framework

A growing body of research highlights the connection between mental health and one's living environment. Cluttered spaces are associated with stress, confusion, and negative affect, whereas tidy spaces can promote clarity and well-being [25-27]. Cleaning and organizing activities are thought to reduce stress by restoring a sense of control and alleviating the cognitive burden of unfinished tasks [28]. Moreover, repetitive household activities such as dishwashing have been linked to increased mindfulness, reduced anxiety, and improved mental inspiration [29].

These findings suggest that cleaning tasks provide a natural context for mindfulness: they are structured, goal-oriented, and yield immediate feedback, which can foster a sense of accomplishment and calm [30]. Importantly, such tasks are low barrier and familiar, making them accessible across diverse populations.

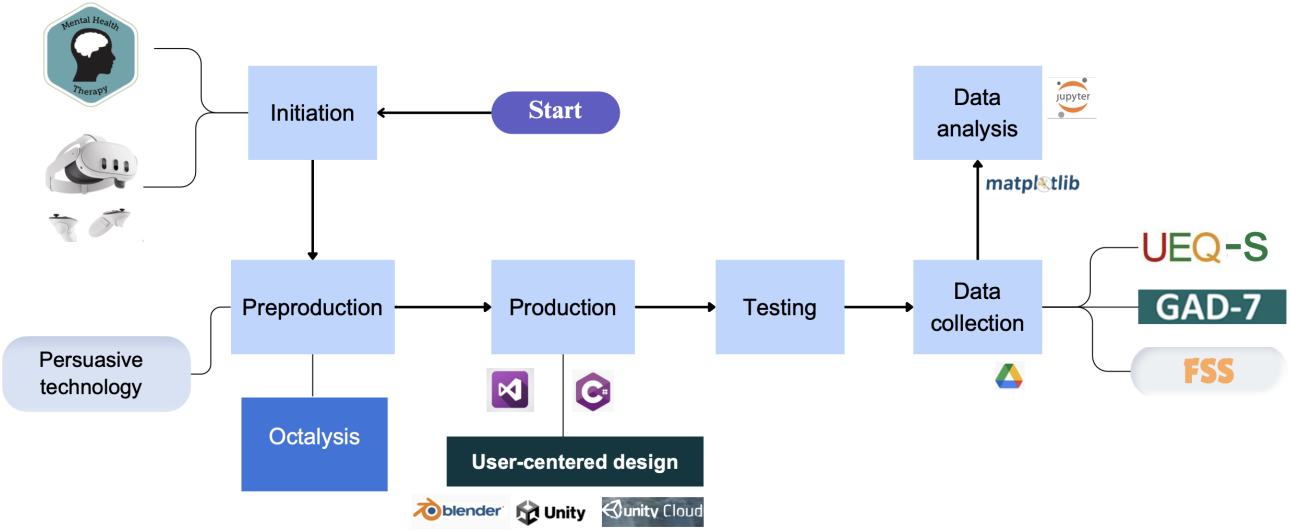
However, the effectiveness of these interventions depends heavily on user engagement. Evidence shows that greater engagement in activities is linked to stronger reductions in anxiety and depression symptoms, with a dose-response relationship observed in cognitive behavioral therapy [31]. Therefore, gamification and persuasive design can play a critical role in sustaining motivation and maximizing the potential benefits of mindfulness-based cleaning activities delivered through VR.

Game Design

Cleanify was developed as a gamified VR experience designed for the Oculus Quest headset (Reality Labs). The application features a 3-level house cleaning simulation structured to progressively engage players in immersive, goal-oriented tasks. The design was guided by the Octalysis framework, which incorporates 8 core motivational drivers to enhance user engagement and sustain motivation (Multimedia Appendix 1). In parallel, the persuasive system design model was applied to integrate persuasive elements that ethically support behavior change and improve user focus. This was particularly relevant given the attentional challenges often experienced by individuals with anxiety [32,33].

The system development process followed 5 phases (Figure 1): initiation (concept development), preproduction (design planning), production (game development with user-centered design), testing (pilot- and usability testing using the Generalized Anxiety Disorder–7 [GAD-7] scale, the short version of the User Experience Questionnaire [UEQ-S], and the Flow State Scale [FSS] tools), and data analysis (evaluation of outcomes).

Figure 1. Flow diagram illustrating the system development and randomized pilot experimental study process of the *Cleanify* virtual reality intervention conducted in Skellefteå, Sweden, in 2024, including initiation, preproduction, production, testing, data collection (Generalized Anxiety Disorder–7 [GAD-7], Flow State Scale [FSS], short version of the User Experience Questionnaire [UEQ-S]), and statistical analysis among young adults with mild anxiety symptoms.



Game Elements and Their Potential Effects on User Engagement and Well-Being

Overview

Cleanify integrates several game elements designed to enhance user focus, engagement, and immersive experience within a virtual environment. Rather than functioning as a clinical treatment, these elements aim to support attentional engagement and promote a calming, structured activity that may be beneficial for individuals experiencing mild anxiety symptoms. An overview of the game's components and their intended experiential functions is provided below. Screenshots of selected components are included in Multimedia Appendices 2 and 3.

Interactive Elements

The *Cleanify* application gives users access to a comfortable VR home with various interactive household necessities. Users can interact with these items in a natural way, which helps the virtual home feel more realistic. Instructions in the game offer different interactive tasks, which can help distract players from their worries and provide a sense of purpose [34]. In addition, gentle reminders to keep calm and relax are placed in different room areas. This helps maintain focus on the present and mindfulness [35].

Physical Movement

In the VR game, players must move around a room to clean up dirt stains, place trash in the trash can, and arrange objects. This engages players in physical activity that releases endorphins, leading to an improvement in anxiety and depression symptoms [36].

Organizing a Space

Cleanify enables players to experience a sense of relaxation and satisfaction through VR immersive technology. Organizing the space into a visually appealing environment increases feelings of well-being [29]. This feeling is further enhanced by different sound and visual effects, providing positive reinforcement that can improve mood and self-esteem [37]. Seeing dirt being removed or trash disappear followed by immediate positive feedback shows players the effectiveness of their efforts, which enhances motivation and satisfaction [38].

Level Progression

The VR game offers structured progression through levels with distinct objectives and benchmarks. This gives the entire gaming experience a sense of regularity and order [39]. Establishing these structured routines may help reduce perceived stress symptoms [40]. Moreover, completing the tasks under each level gives players a sense of achievement, which reduces stress [41].

Controlled Environment

Cleanify empowers players, providing a sense of control over their surroundings [42]. Additionally, the VR game's second and third levels include time-limited challenges. This helps players practice coping with pressure in a safe environment [43].

Game Scoring

Depending on the player's performance, the VR application offers several scoring systems, including stars, badges, and a scoreboard for high scores. These components increase focus on and engagement in tasks [44]. Displaying the top scorers enables players to view their rankings and compare their progress with that of others [45].

Participant Recruitment and Research Process

Participants were recruited between April 2024 and May 2024 from the general population in the municipality of Skellefteå in northern Sweden through multiple channels, including social media announcements, local community centers, and student Discord groups. Interested individuals completed an online screening survey that included demographic questions and the GAD-7 scale to assess anxiety symptom severity. Exclusion criteria were severe psychiatric disorders, epilepsy, or a history of severe motion sickness, ensuring suitability for VR

participation. A total of 54 individuals were recruited; 4 (7.4%) were excluded for not meeting the criteria, resulting in a final sample of 50 (92.6%) participants who were randomized. Studies suggest that 10 to 30 participants per group is usually acceptable for a pilot study [46], and therefore, our sample size aligns with established guidelines.

Prior to the main intervention, all participants underwent a structured onboarding and training session. This included an orientation briefing that explained the study purpose, VR procedures, and safety precautions. Participants were shown a short tutorial video and provided with guided, hands-on practice using the Oculus Quest headset and controllers. It was ensured that each participant demonstrated adequate understanding of headset operation, navigation, and interaction within the VR environment before beginning the intervention. This training minimized variability in participant readiness and helped establish comfort with the VR system.

Instruments

Several standardized instruments were used to assess participant characteristics and user experience outcomes. The GAD-7, a validated self-report measure of anxiety symptom severity, was administered at baseline to characterize participants' anxiety levels prior to the VR session [47]. The UEQ-S was used to evaluate participants' subjective experiences, focusing on usability, immersion, and satisfaction [48,49]. The short version was selected to efficiently capture key user experience dimensions while minimizing participant fatigue. The FSS was used to measure participants' perceived focus and immersion during the VR session [50]. Flow describes a psychological state in which perceived challenges are balanced with individual skills, resulting in deep concentration and intrinsic engagement. It is widely used to evaluate immersive experiences in domains such as gaming, training, and digital applications [51].

Experiment Design

The study began with an overview of its purpose, after which participants provided informed consent. Following demographic and eligibility screening, participants completed the GAD-7 assessment [47]. Screening ensured that participants met the inclusion criteria and had no contraindications for VR use, such as epilepsy or severe motion sickness.

Participants were randomly assigned to either the gamified or nongamified group using a simple randomization method with a 1:1 allocation ratio. No blocking or stratification was applied. Group allocation was revealed to participants only at the time of the intervention. Due to the visible differences between versions, participants were not blinded to group allocation. The researcher overseeing data collection was also aware of group assignments; however, data analysis was conducted without access to condition labels until completion of the primary analyses.

Each participant then engaged in a single 15-minute VR session. No external prompts or reminders were used to encourage participant engagement; all guidance and prompts were embedded within the VR application in the form of task instructions and in-environment reminders.

Questionnaire Design

A Google Forms questionnaire structured into 5 sections was used for data collection. The first section provided an explanation of the study purpose and procedures and included informed consent information, emphasizing voluntary participation, data confidentiality, and the right to withdraw at any time. The second section collected demographic information, including age, gender, and occupation.

The third section consisted of the GAD-7 scale, which assesses the frequency of anxiety-related symptoms over the preceding 2 weeks [52]. The fourth section included 8 items from the UEQ-S measured on a 7-point Likert scale, assessing usability, immersion, and overall user experience [48]. The fifth section comprised the FSS, consisting of 13 items measured on a 7-point Likert scale to assess focus and immersion during the VR experience [50].

In addition to these standardized instruments, 2 engagement-related measures were included. Level reached was used as an objective indicator of in-game engagement and referred to the highest level (levels 1 - 3) completed by each participant during the 15-minute VR session. The *Cleanify* VR application consists of 3 sequential levels of increasing task complexity. Recommendation score was used as a subjective measure of user satisfaction and was collected by asking participants to rate their likelihood of recommending the *Cleanify* VR application to others on a 5-point Likert scale (1="strongly disagree"; 5="strongly agree").

The complete set of questionnaire items used in this study, including the GAD-7, FSS, and UEQ-S items, is provided in Multimedia Appendix 4.

Data Analysis

All data were collected using Google Forms. All responses were collected anonymously, and no personally identifiable information was recorded. Access to the data was restricted to the research team, and data handling procedures complied with institutional data protection guidelines. Participants completed the questionnaires both before and after the 15-minute VR session by scanning a QR code with their smartphones and completing the forms on-site. The data were subsequently exported to Google Sheets for analysis. Analyses were performed using Python (version 3.0; Python Software Foundation) with standard libraries (pandas and NumPy). Descriptive statistics were calculated to summarize participant demographics, baseline anxiety levels (GAD-7 scores), and engagement metrics such as level reached and session duration. Means, SDs, and percentages were reported where appropriate.

Inferential statistical tests were conducted to compare outcomes between the 2 conditions (gamified vs nongamified). Two-tailed independent-sample *t* tests were used to assess differences in continuous variables, including flow, worry, fluency, and absorption scores from the FSS as well as user experience scores from the UEQ-S. Statistical significance was set at an α level of .05.

Assumptions of normality were considered when selecting statistical tests. Data distributions were assessed using

descriptive inspection and skewness values. Given the exploratory nature of this pilot study and the approximately balanced group sizes, independent-sample *t* tests were applied as they are robust to moderate deviations from normality.

Baseline GAD-7 scores were used for descriptive purposes only to characterize anxiety symptom severity within the sample, and no inferential statistical tests were applied to these variables. For ordinal variables such as level reached, descriptive comparisons were used instead of parametric statistical testing.

Ethical Considerations

This study was conducted in accordance with the World Medical Association's International Code of Medical Ethics (Declaration of Helsinki). The well-being of participants was prioritized before, during, and after the intervention. Participants were provided with clear information about the study's purpose and procedures and any potential risks, enabling them to make informed decisions about their involvement. Informed consent was obtained directly from all young adults prior to data collection, and they were informed of their right to withdraw at any time without consequence. Participants did not receive any compensation for their involvement in this study.

No personally identifiable information was collected; only limited demographic details (age, gender, occupation, and prior VR experience) were recorded. All responses were collected anonymously via Google Forms, stored securely, and accessible only to the research team, ensuring participants' privacy and confidentiality.

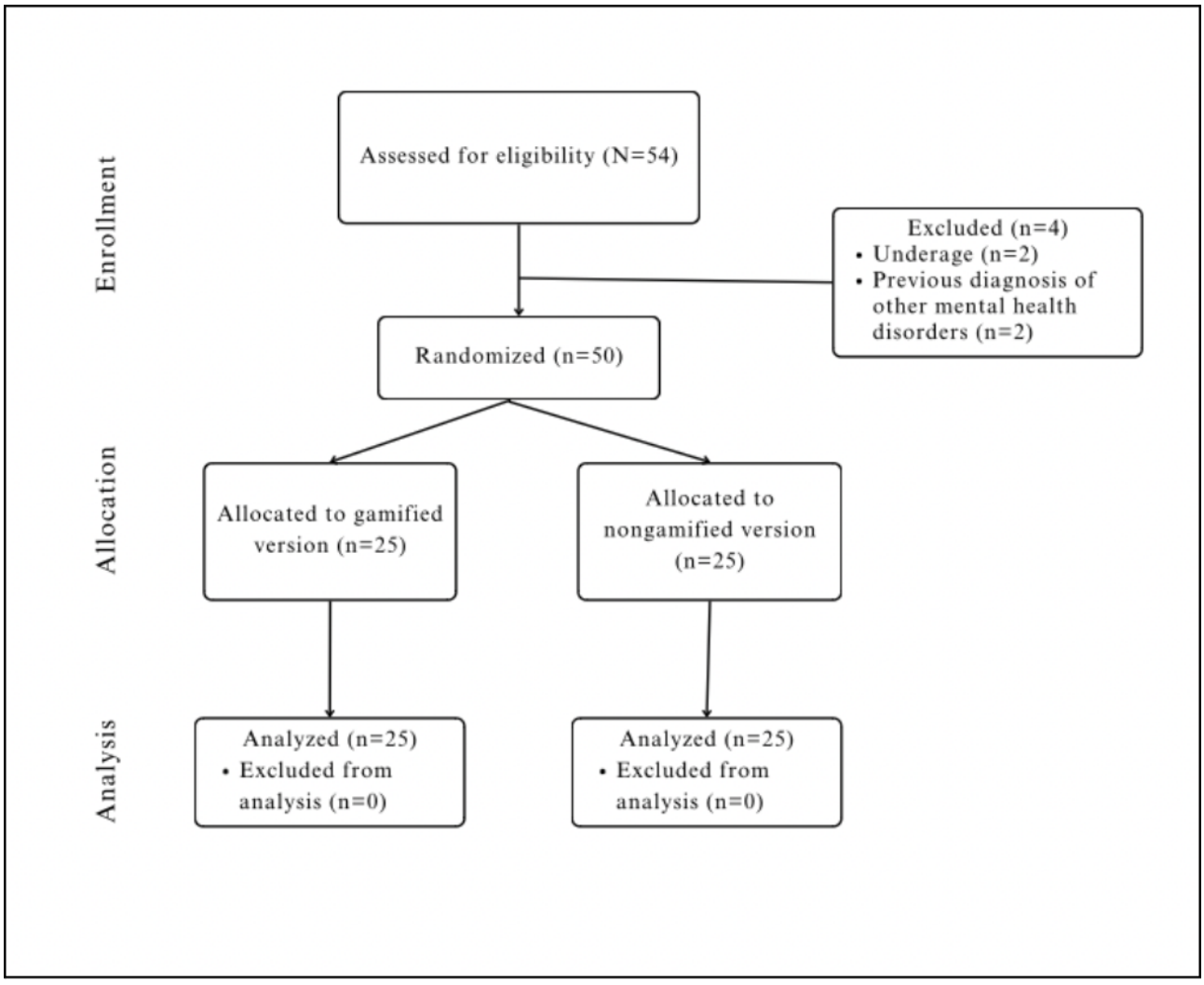
Given the nonclinical nature of the study, the use of anonymous data, and the minimal risk to participants, formal ethics approval was not obtained. However, the study adhered to standard ethical principles for human subject research.

Results

Participant Flow

Figure 2 illustrates the flow of participants through the study, including recruitment, exclusions, randomization, and final allocation to the gamified and nongamified conditions.

Figure 2. Participant flow diagram of the randomized pilot experimental study conducted in Skellefteå, Sweden, in 2024 showing screening, exclusions, randomization, and allocation to gamified and nongamified virtual reality intervention groups among young adults aged 18 to 39 years with mild anxiety symptoms.



Participant Demography

Table 1 summarizes the demographic characteristics of the study participants. A total of 50 individuals took part in the study, representing a diverse sample in terms of age, gender, occupation, and prior experience with VR.

Table . Demographic characteristics of participants enrolled in a randomized pilot experimental study conducted in Skellefteå, Sweden, in 2024 evaluating gamified vs nongamified virtual reality (VR) interventions (N=50).

Variable	Participants, n (%)
Gender	
Man	29 (58)
Woman	21 (42)
Nonbinary	0 (0)
Age (y)	
18-25	12 (24)
25-39	38 (76)
Occupation	
Student	28 (56)
Professional	22 (44)
Prior experience with VR	
Yes	30 (60)
No	20 (40)

Baseline Characteristics

Table 2 provides a comparison of baseline demographic and anxiety-related characteristics between the gamified and nongamified groups. Variables include age, gender, occupation, prior VR experience, and mean baseline GAD-7 scores. Independent-sample *t* tests and chi-square analyses were conducted to assess potential group differences.

Table . Baseline demographic and clinical characteristics of participants randomized to the gamified and nongamified groups in a pilot experimental study conducted in Skellefteå, Sweden, in 2024.

Variable	Gamified (n=25)	Nongamified (n=25)	Test statistic		*P* value
			t test (*df*)	Chi-square (*df*)	
Age (y), mean (SD)	29.1 (4.9)	29.0 (5.0)	0.09 (48)	—[a]	.93
Gender, n (%)			—	0.3 (1)	.56
Man	17 (68)	14 (56)			
Woman	8 (32)	11 (44)			
Occupation, n (%)			—	0.7 (1)	.39
Student	16 (64)	12 (48)			
Professional	9 (36)	13 (52)			
Prior VR[b] experience, n (%)	14 (56)	16 (64)	—	0.08 (1)	.77
GAD-7[c] score (0-21), mean (SD)	6.8 (5.9)	6.9 (5.3)	–0.10 (48)	—	.92

[a]Not applicable.

[b]VR: virtual reality.

[c]GAD-7: Generalized Anxiety Disorder–7.

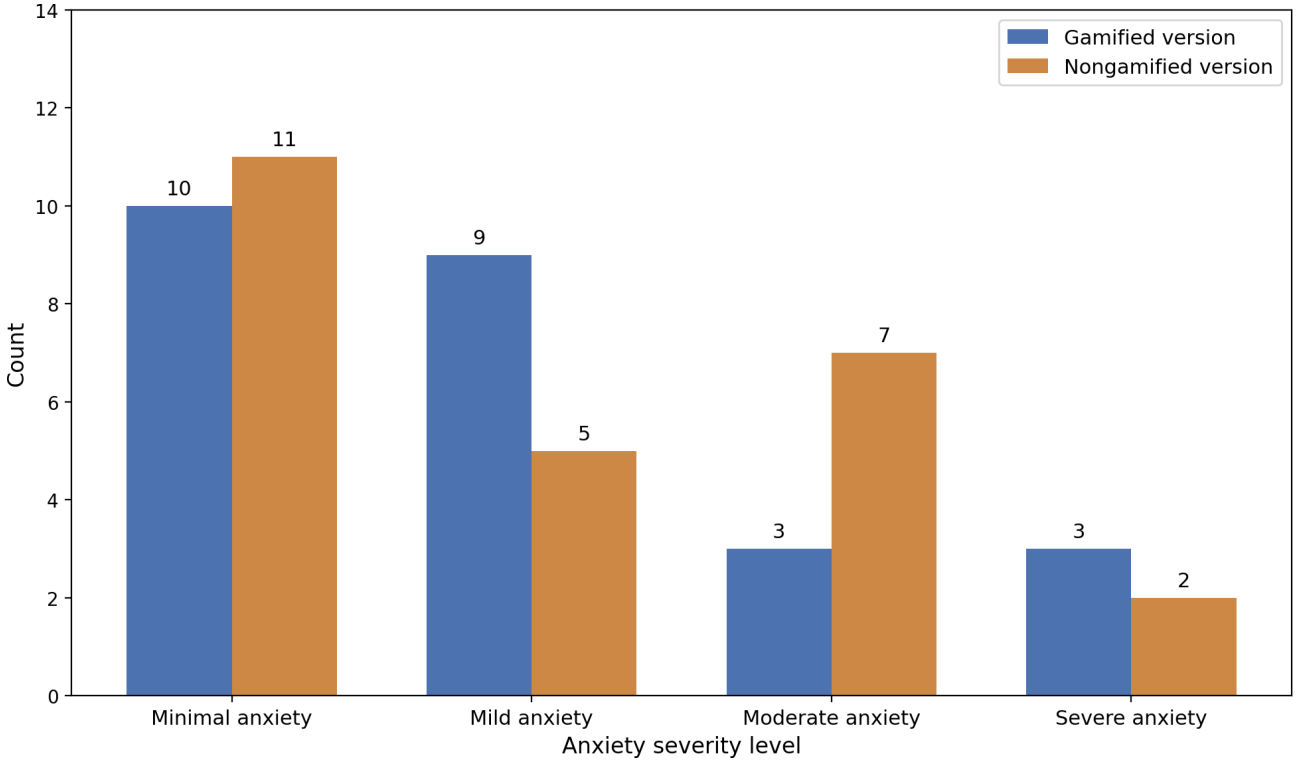
The results indicated no statistically significant differences between groups on these baseline variables, supporting comparability prior to the intervention.

GAD-7 Score

The GAD-7 results were used for descriptive analysis to provide an overview of participants' anxiety levels before engaging with the *Cleanify* VR application. The data collected allowed for the assessment of baseline anxiety symptoms within the participant

group. This offered insights into the overall mental health status of the individuals involved. However, it is important to note that the study did not include a postintervention assessment, so the GAD-7 results primarily describe the participants' anxiety profiles rather than measuring changes resulting from the intervention. Figure 3 shows the distribution of anxiety levels between the 2 groups. It highlights the variations in minimal, mild, moderate, and severe anxiety levels among the participants. This visual representation underscores the diversity of anxiety experiences within the study population.

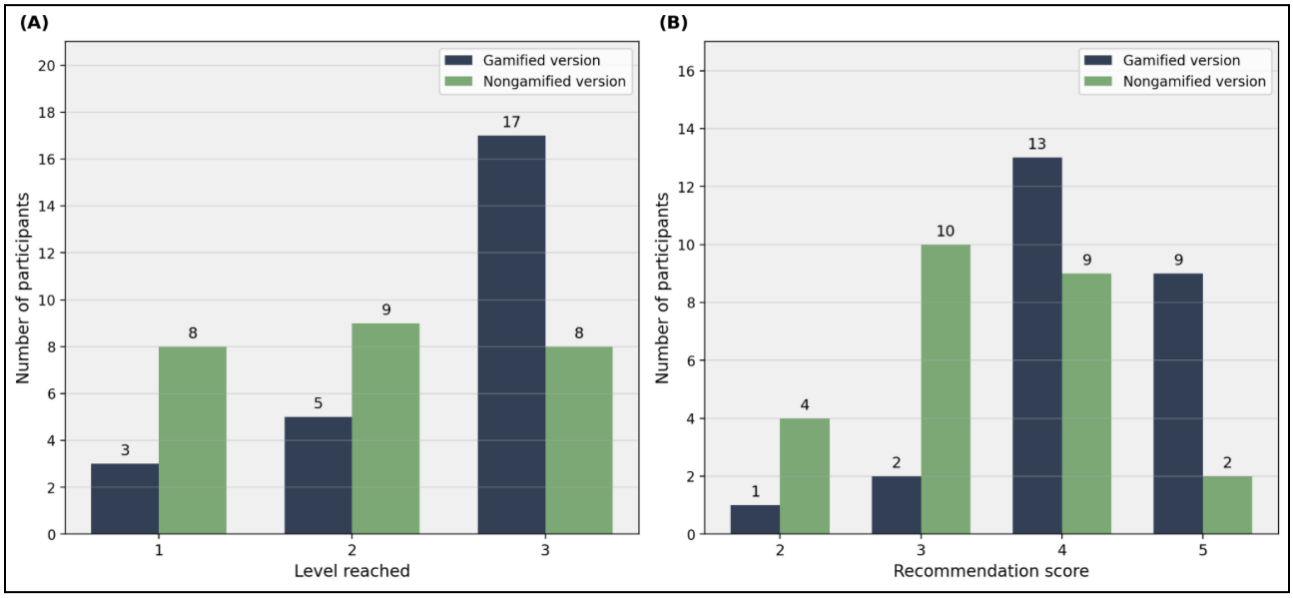
Figure 3. Distribution of baseline anxiety severity levels (minimal, mild, moderate, and severe) measured using the Generalized Anxiety Disorder–7 scale among young adults (N=50) in Skellefteå, Sweden, in 2024 randomized to gamified and nongamified virtual reality conditions.



User Experience

During the intervention, the level reached by participants was recorded as an indicator of engagement within the VR experience. As illustrated in Figure 4, differences in level progression between the 2 groups highlight variations in user engagement. A higher proportion of participants in the gamified group reached level 3 (17/25, 68.0%) than in the nongamified group (8/25, 32.0%), indicating greater progression and interaction with the game. This pattern suggests that gamification elements supported increased engagement during the session.

Figure 4. Comparison of engagement outcomes between the gamified and nongamified virtual reality groups in a pilot experimental study conducted in Skellefteå, Sweden, in 2024: (A) the distribution of the highest levels reached (levels 1 - 3) and (B) recommendation scores (5-point Likert scale).

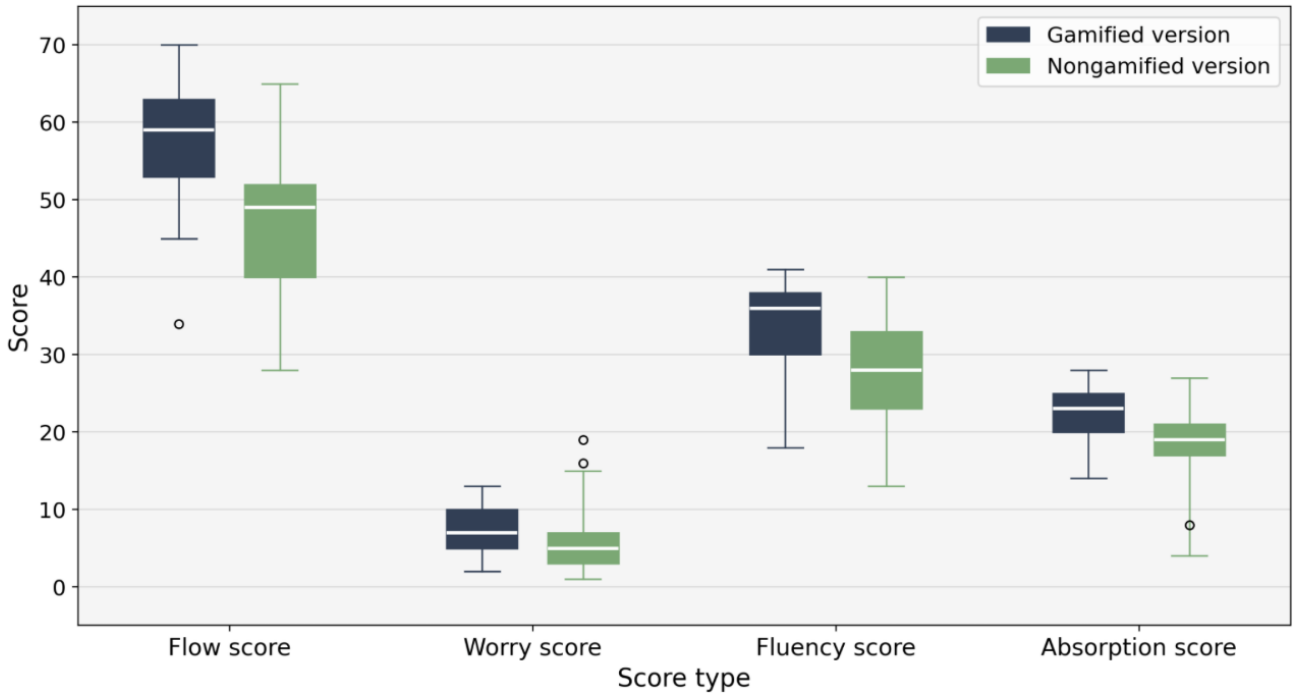


After performing the intervention, participants were asked whether they would recommend the application to others as an indicator of user experience. Participants in the gamified group reported a higher average recommendation score (4.20, SD 0.76) than the nongamified group (3.36, SD 0.86), with 36.0% (9/25)of the participants in the gamified group giving a top score of 5 compared to 8.0% (2/25) (n/N) in the nongamified group. These findings suggest that the gamified elements of *Cleanify* enhanced participants' enjoyment of the application, increasing their likelihood of recommending it to others.

User Focus and Immersion Analysis

The FSS scores showed significant differences between the 2 groups (Figure 5; α=.05; flow score: t_{48}=3.87 and P<.001; worry score: t_{48}=1.66 and P=.10; fluency score: t_{48}=4.36 and P<.001; absorption score: t_{48}=2.80 and P=.008).

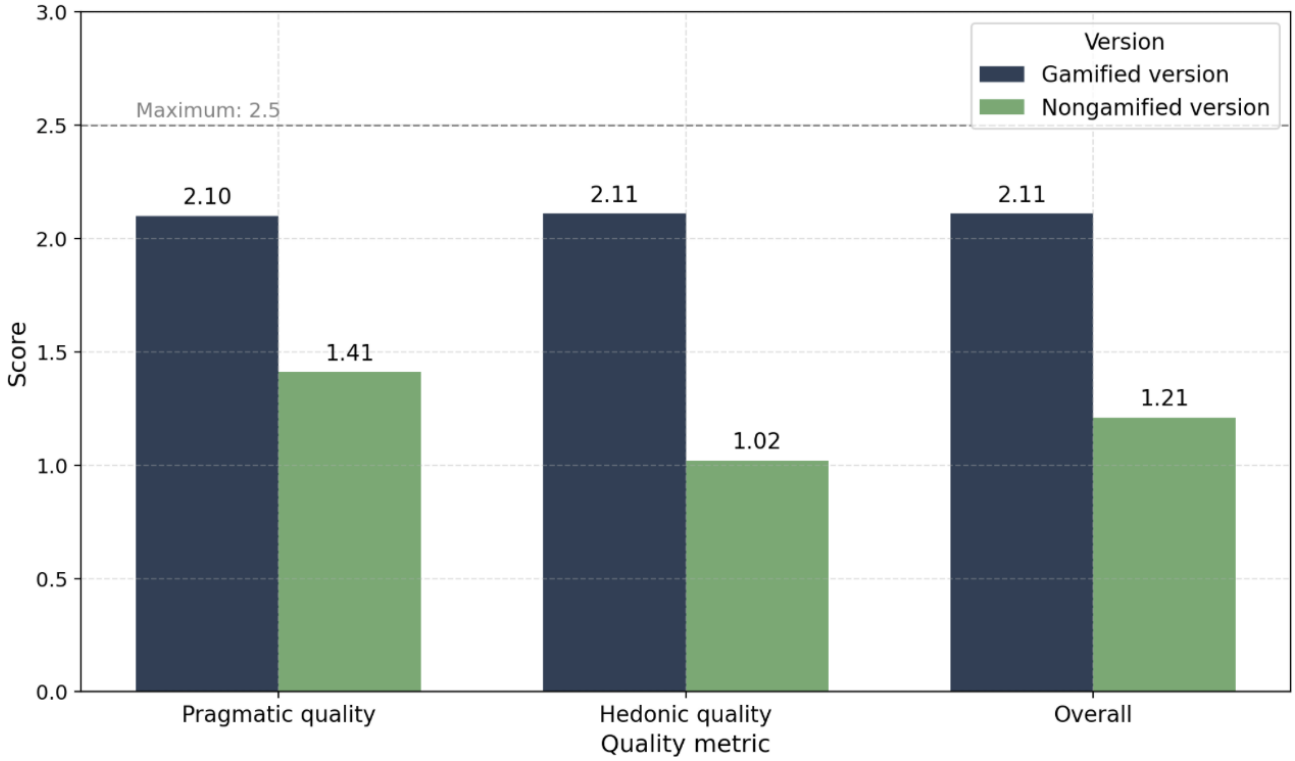
Figure 5. Comparison of Flow State Scale subscale scores (flow, worry, fluency, and absorption) between the gamified and nongamified virtual reality (VR) groups in a randomized pilot experimental study conducted in Skellefteå, Sweden, in 2024. Box plots display the distribution of postintervention scores following a single 15-minute VR session.



User Engagement and System Usability Analysis

UEQ-S data showed higher scores in the gamified version across pragmatic quality (mean 2.10, sd 0.92 vs mean 1.41 , sd 0.98), hedonic quality (mean 2.12 , sd 1.06 vs mean 1.01, sd 1.07), and overall quality (mean 2.11, sd 0.92 vs mean 1.21, sd 0.92 ; Figure 6). These differences indicate improved user experience in the gamified condition. However, as statistical significance testing was not conducted for UEQ-S subscales, these findings should be interpreted as descriptive comparisons.

Figure 6. Scores on the short version of the User Experience Questionnaire comparing pragmatic quality, hedonic quality, and overall user experience between gamified and nongamified versions of a virtual reality application in a randomized pilot study conducted in northern Sweden in 2024.



Discussion

Principal Findings

This study explored how gamification influences user engagement, focus, and immersion in a VR application designed for individuals with generalized anxiety symptoms. Results from the FSS indicated significant differences between groups: participants using the gamified version reported higher levels of flow, immersion, and absorption than those using the nongamified version. These findings suggest that gamified elements facilitated deeper engagement, with users becoming more absorbed in the activity and experiencing smoother, more cohesive interactions. Importantly, worry scores were low across both conditions, indicating that participants generally experienced the task as calming and focused.

User experience ratings (UEQ-S) were also higher in the gamified version across both pragmatic and hedonic dimensions, underscoring that gamification improved usability, satisfaction, and enjoyment. Collectively, these findings highlight that gamification enhanced the subjective quality of the VR experience.

Nevertheless, this study was not designed to evaluate therapeutic efficacy. While gamification clearly increases focus and engagement, the absence of postintervention measures of anxiety, stress, or mindfulness prevents conclusions about clinical benefits. Baseline equivalence across demographic characteristics and GAD-7 scores helps rule out preexisting differences as drivers of the results, but therapeutic impact remains untested.

Comparison to Prior Work

These results align with those of prior literature demonstrating that gamification enhances motivation, engagement, and user experience in nongame contexts [16,53]. The higher flow, fluency, and absorption scores in the gamified condition echo findings that game elements—such as challenges, feedback, and rewards—can deepen user involvement and sustain attention [54]. Similarly, the higher pragmatic and hedonic scores mirror earlier work linking gamification to both improved functionality and enjoyment [55,56].

Together, these findings extend existing knowledge by showing that gamified VR environments can support more engaging and satisfying experiences for individuals with generalized anxiety symptoms. They support the proposition that integrating game design elements into VR tools creates more compelling environments, although clinical benefits require further investigation.

Limitations and Future Work

Several limitations temper the interpretation of these findings. First, this study was exploratory and focused primarily on engagement, immersion, and usability rather than clinical outcomes. Therefore, the findings should not be interpreted as evidence of therapeutic efficacy.

Second, the observed levels of engagement and positive user experience may have been influenced by a novelty effect associated with the VR environment. Participants' responses could partly reflect the initial excitement or unfamiliarity with immersive VR technology rather than stable or sustained engagement attributable to the intervention itself. As the study design did not include repeated exposure or long-term follow-up, it is not possible to distinguish the effects from enduring

behavioral or experiential changes. Therefore, any implications regarding improved adherence or sustained engagement should be interpreted with caution.

Third, recruitment was resource constrained and limited to community participants in northern Sweden. Although random assignment helped mitigate selection bias, most participants did not have a clinical diagnosis of anxiety disorder. Future research should include clinically diagnosed populations to better evaluate the therapeutic relevance and applicability of the intervention.

Fourth, the intervention consisted of a single 15-minute session, which limits insights into sustained engagement, habituation effects, or long-term impact. Other studies incorporating repeated sessions are necessary to assess whether engagement and perceived benefits persist beyond initial exposure.

Fifth, the broad age range of the participants (18 - 39 years) may have influenced how individuals related to the cleaning-based tasks as perceptions of relevance and motivation can vary across life stages.

Finally, as the study did not include postintervention measures of anxiety, stress, or mindfulness, it is not possible to determine whether the observed increases in engagement translate into measurable psychological or therapeutic outcomes. To address this limitation, future research should incorporate both pre- and postintervention assessments using validated psychological instruments, ideally within a controlled clinical trial design. Longitudinal studies with repeated exposure sessions would further help determine the durability of engagement effects. Such designs would allow for a more comprehensive evaluation of both usability outcomes and potential clinical effectiveness.

Conclusions

This study aimed to develop and evaluate a gamified VR application designed to support individuals experiencing mild anxiety by enhancing engagement, focus, and immersion. The findings indicate that incorporating gamification and persuasive design elements significantly improved user experience metrics, including perceived flow and satisfaction, compared to the nongamified version.

As the study focused on engagement-related outcomes and did not include postintervention anxiety assessments, the results should not be interpreted as evidence of clinical effectiveness. Rather, the findings demonstrate that gamified VR environments can successfully increase user immersion and interaction quality in short-term exposure settings.

User feedback further highlighted the importance of audiovisual design quality and appropriate challenge levels in maintaining engagement. These insights contribute to the growing body of research exploring how immersive technologies can be optimized to enhance user experience in mental health–related applications.

Overall, this study provides empirical evidence that gamification strategies can positively influence engagement and immersion within VR-based applications targeting individuals with mild anxiety.

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Data Availability

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

Authors' Contributions

Conceptualization: MMA, SSO, NJ
Data curation: MMA
Funding acquisition: SSO, NJ, MBTN
Investigation: MMA, NJ, SSO
Methodology: MMA, NJ, SSO, MBTN
Project administration: MMA, NJ, SSO, MBTN
Resources: MMA
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Validation: MMA, NJ, SSO, MBTN
Writing—original draft: MMA, NJ, SSO
Writing—review and editing: MMA, NJ, SSO, MBTN
All authors contributed to the article and approved the submitted version.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Implementation of the Octalysis core drivers in the *Cleanify* virtual reality application.
[DOCX File, 8 KB - xr_v3i1e66713_app1.docx]

Multimedia Appendix 2
Level 3—space organization layout.
[PNG File, 1061 KB - xr_v3i1e66713_app2.png]

Multimedia Appendix 3
Badge and star reward system in the *Cleanify* virtual reality application.
[PNG File, 461 KB - xr_v3i1e66713_app3.png]

Multimedia Appendix 4
Full questionnaire items.
[DOCX File, 8 KB - xr_v3i1e66713_app4.docx]

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Abbreviations

FSS: Flow State Scale
GAD-7: Generalized Anxiety Disorder–7
UEQ-S: short version of the User Experience Questionnaire
VR: virtual reality

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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.

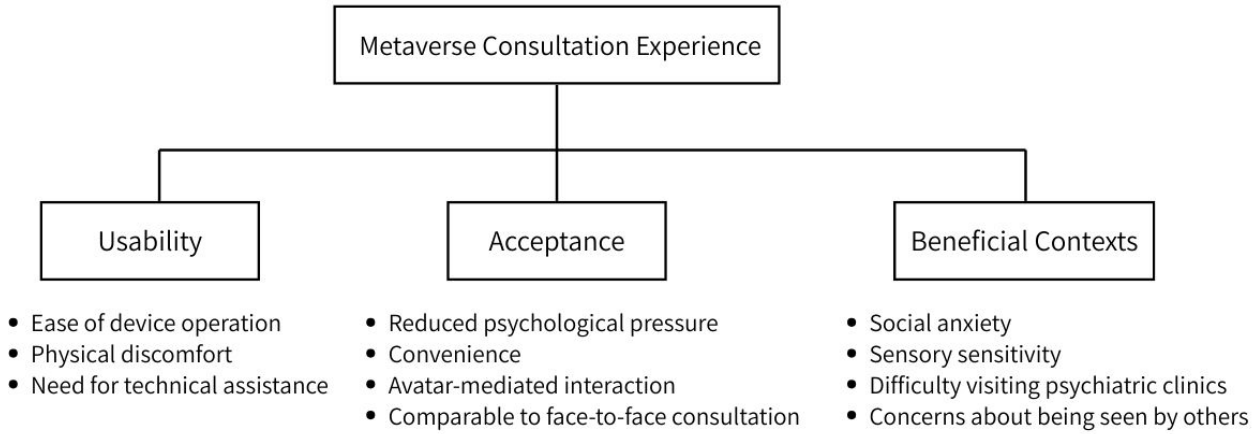
Aspect of assessment	Summary of findings
1. Physical and psychological condition	
Perceived health issues	Most participants (21/26, 80%) indicated concerns about their physical or mental health, with common issues including insomnia, social anxiety, general anxiety, depression, learning disabilities, 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
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Formal analysis: MI, JF, NT
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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.

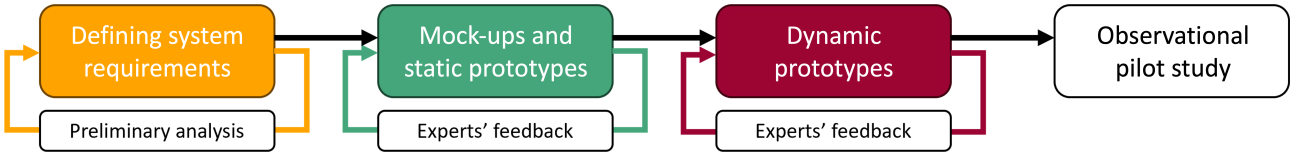
Study Design: Experimental Setting

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.

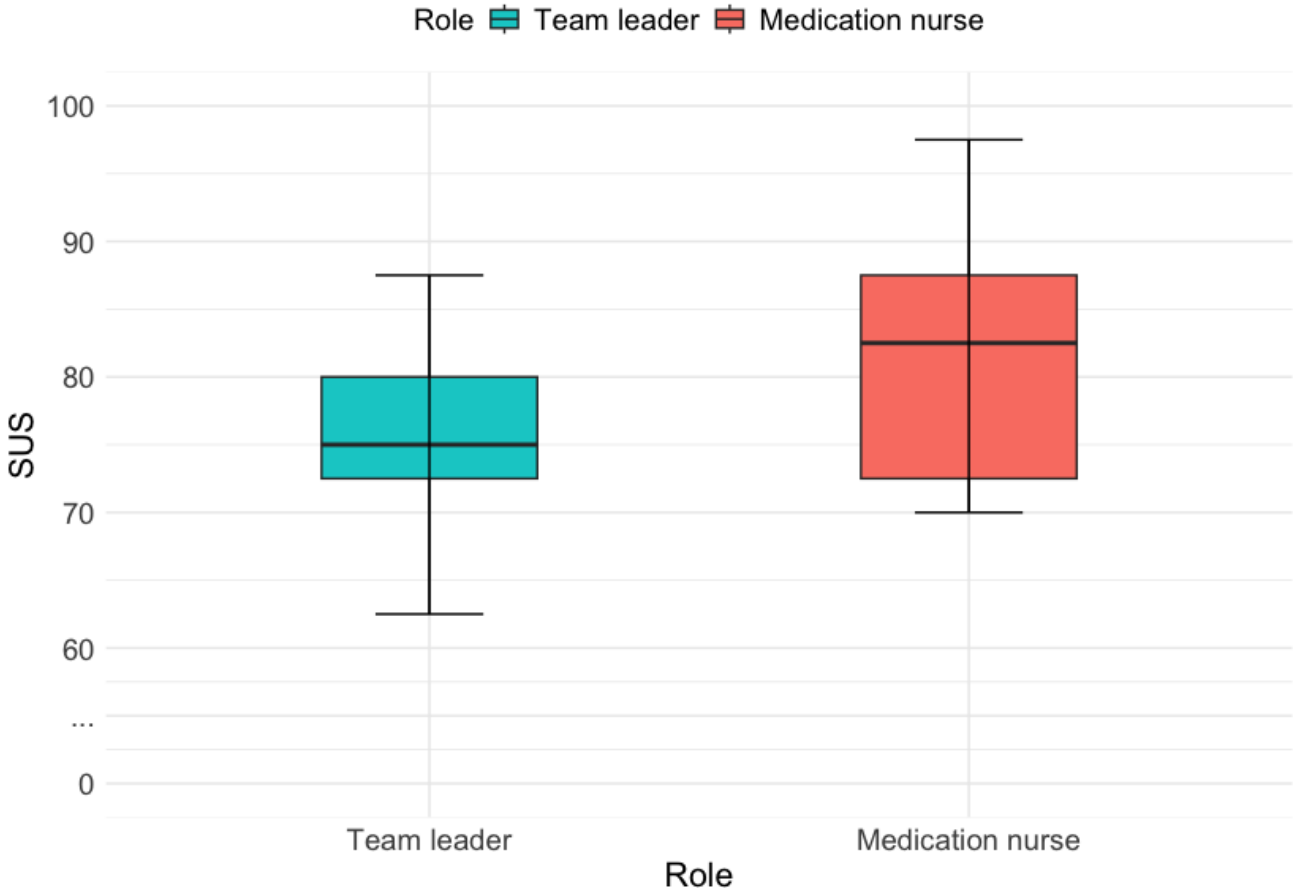
Table . Participant demographics.

	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.



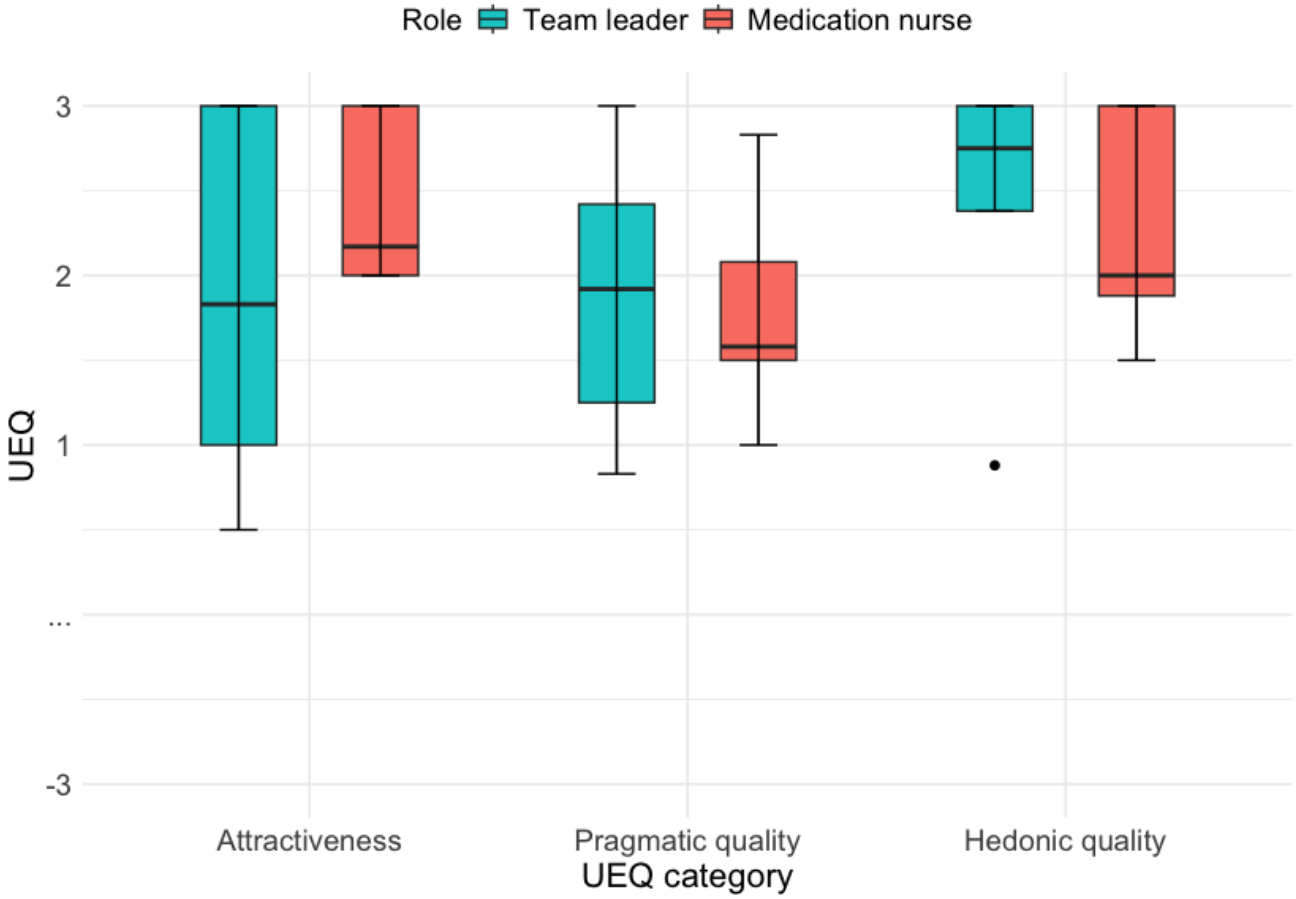
The medication nurse role achieved a higher mean score of 82.00 (SD 11.20, SE 5.02, 95% CI 68.00-96.00), corresponding to an "A" grade (80.80 - 84.00), which falls within the "excellent" usability range (Multimedia Appendix 2). Although the point estimate suggests a stronger perceived usability for medication 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,

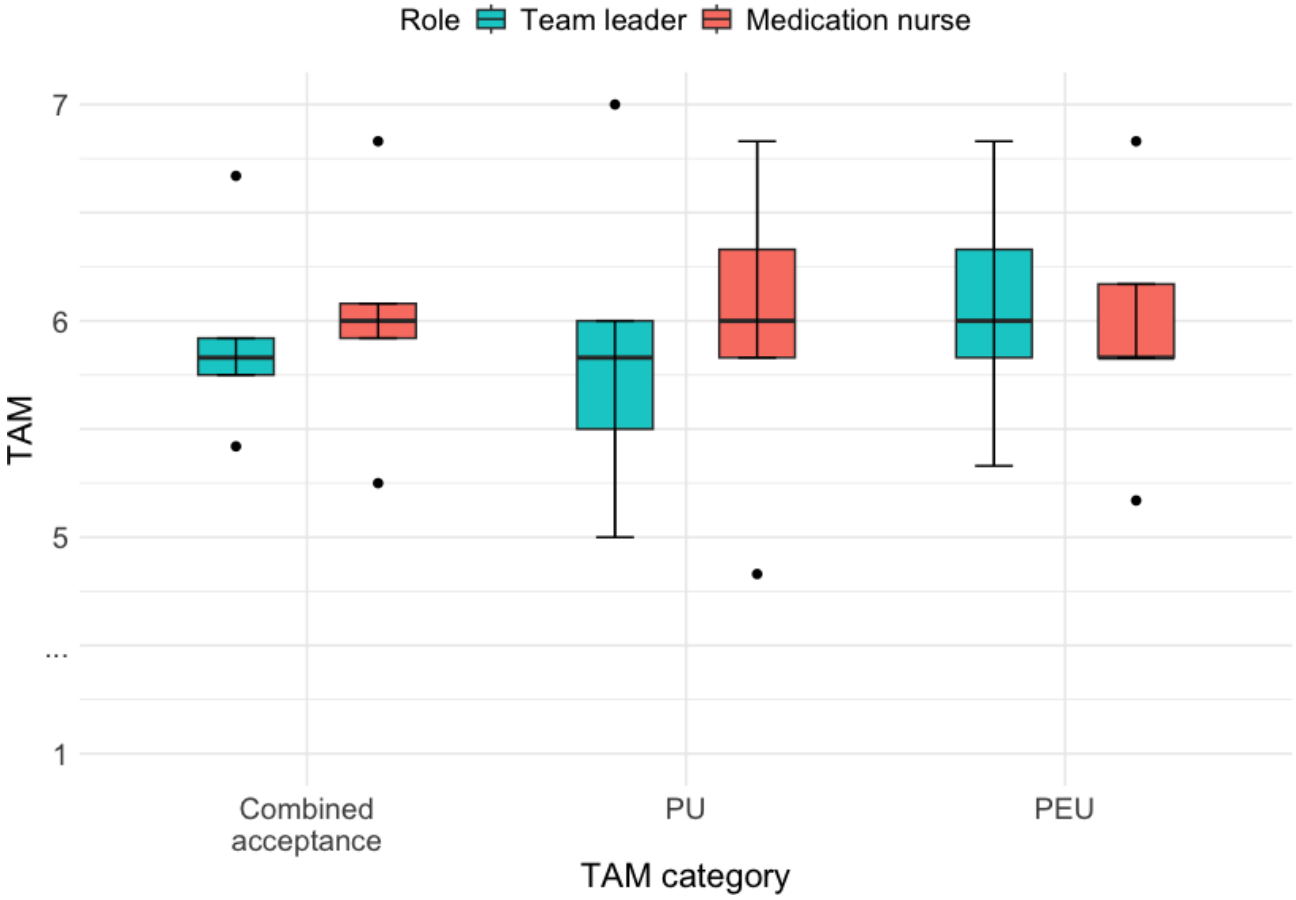
motivating them throughout its use, but overlapping CIs and moderate width reflect limited precision in this pilot evaluation.

- 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."

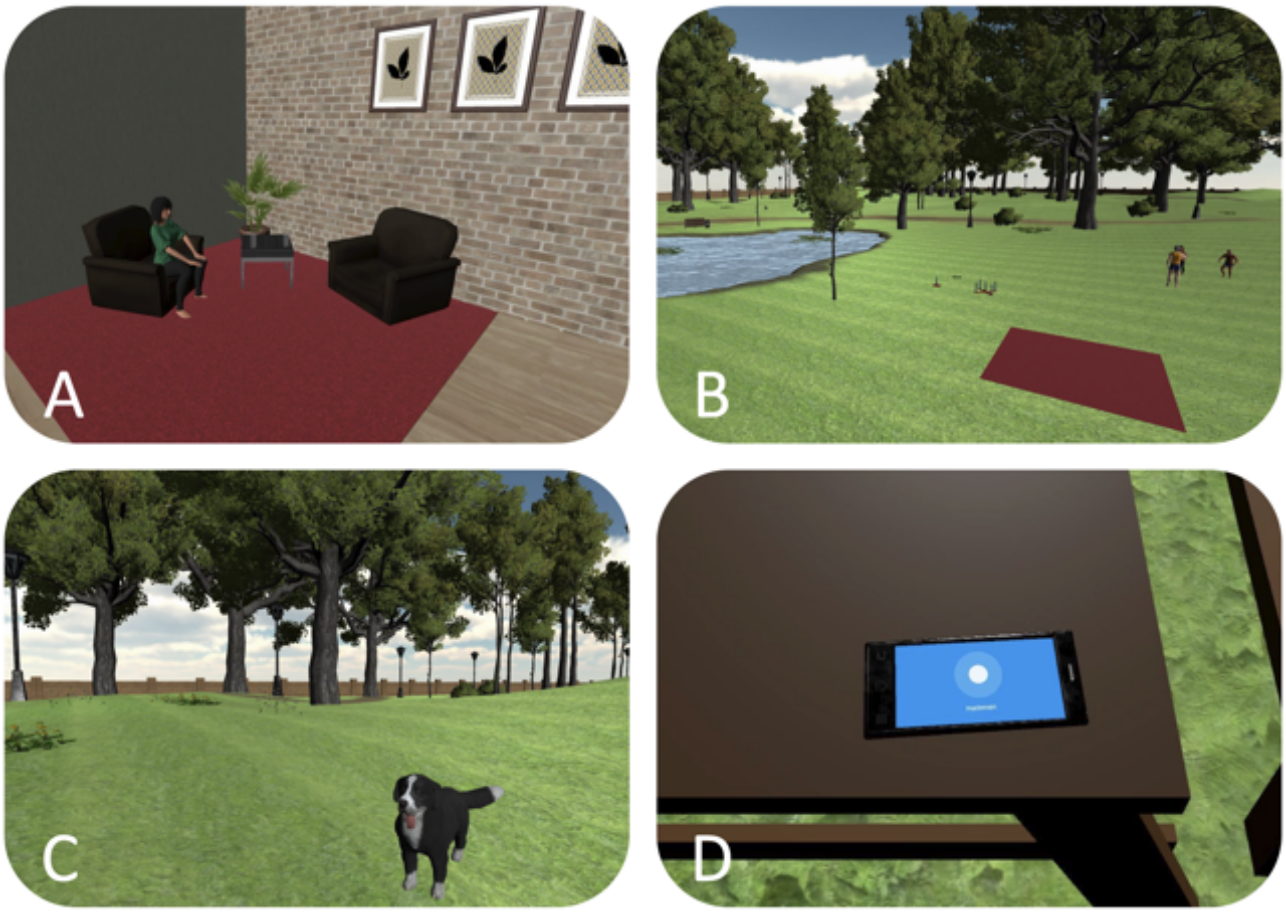
A semistructured interview (Multimedia Appendix 2) with 14 open questions was conducted to explore (1) VE to induce and reduce nicotine craving (3 questions), (2) explored coping strategies to reduce nicotine craving (5 questions) and alternatives in IVR to reduce nicotine craving (5 questions), and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

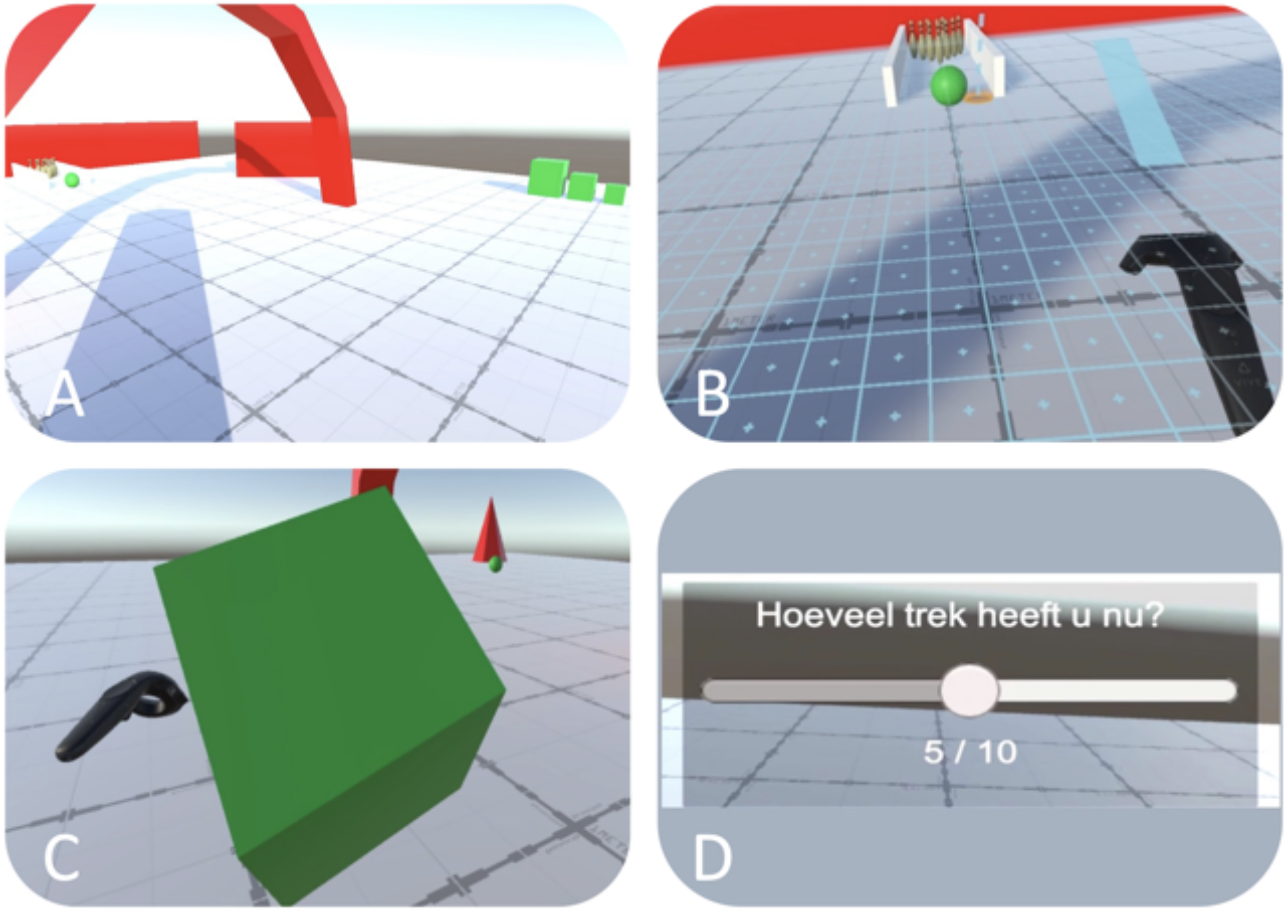
The VE was developed in Unity3D (v.2019.2.3f1; Unity Technologies) using the SteamVR Software Development Kit (Valve Corporation) and was partially adapted from previous work by our department [13], containing two main scenarios: (1) craving induction and (2) reduction (see Figures 1A-1D). The craving 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.

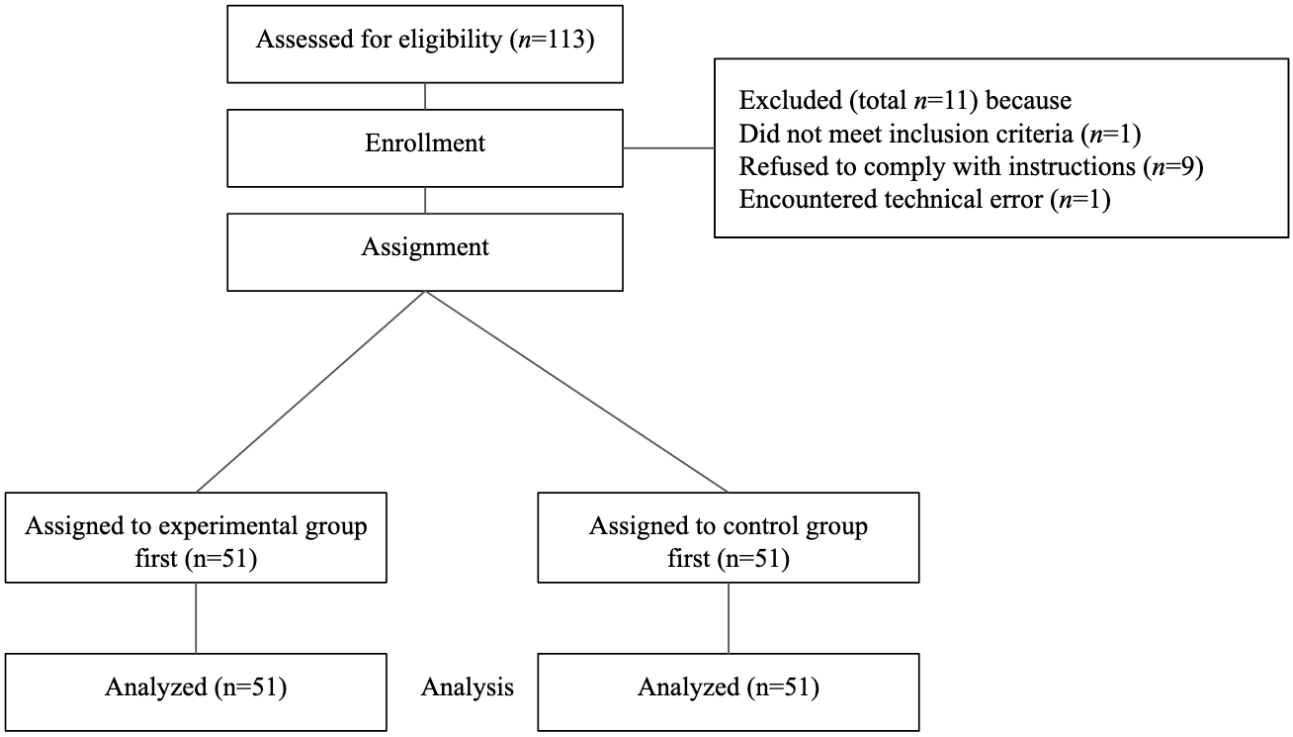


Table . Demographic characteristics of the sample (N=102) in a within-subjects experiment comparing brief VR[a] and MR[b] mindfulness breathing and a mind-wandering control.

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).

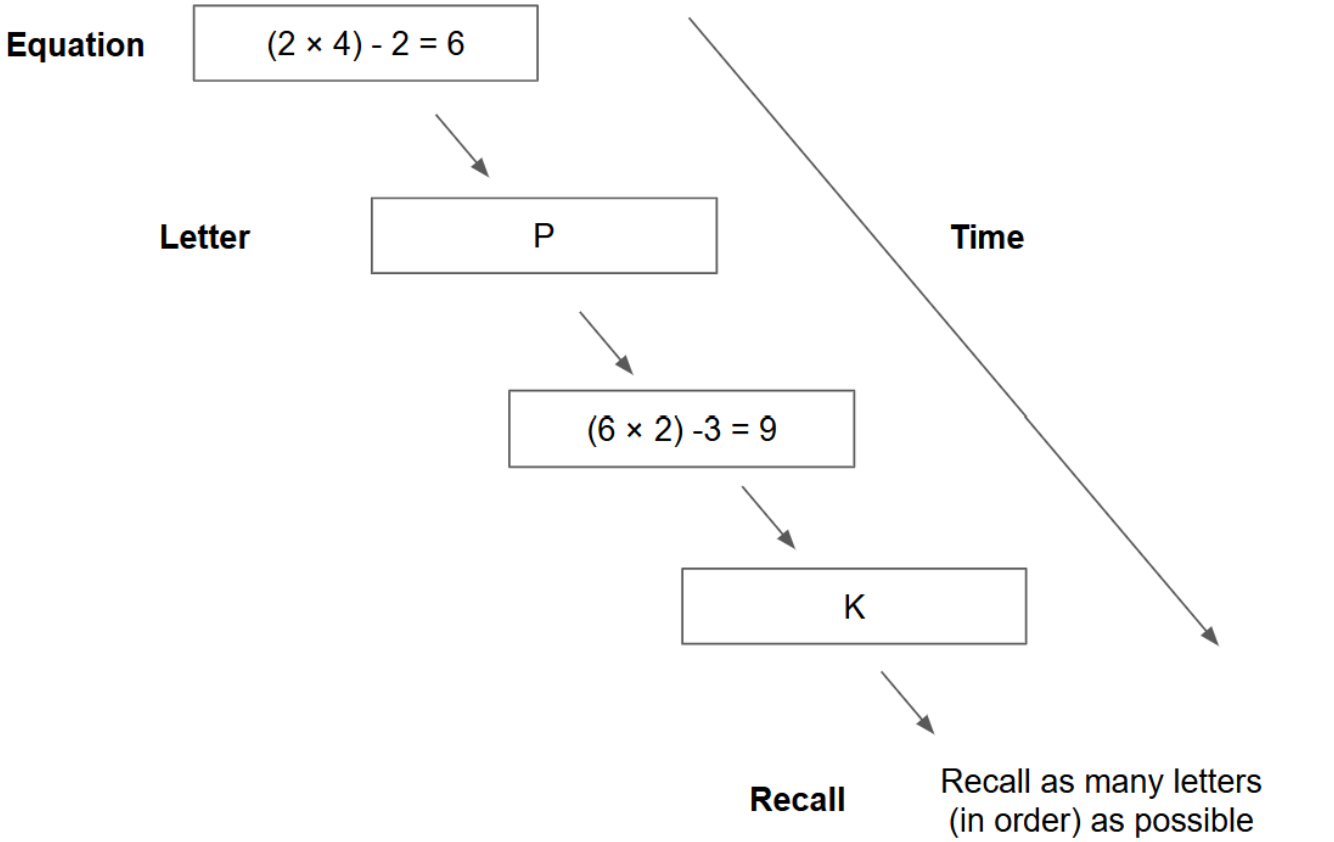
Working Memory Tasks

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.

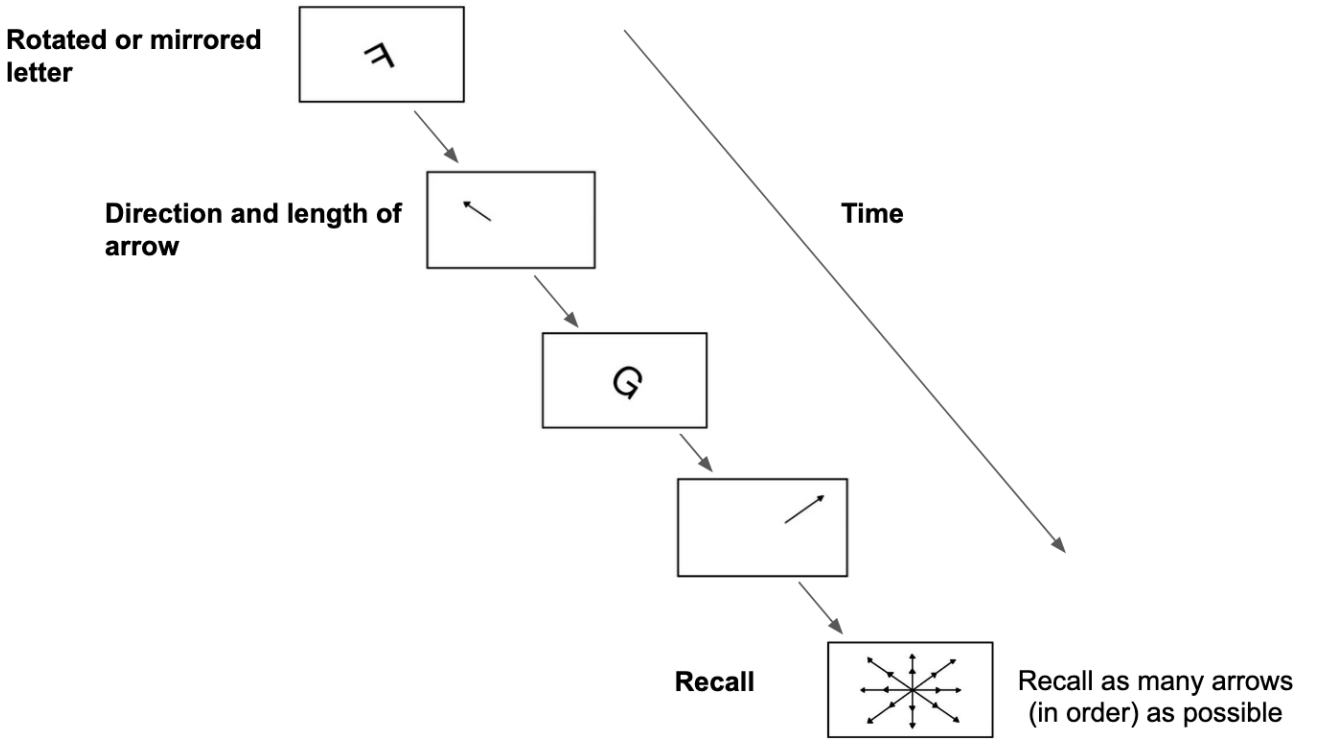
Baseline working memory capacity was assessed using the OSpan task. In this task, participants solved mathematical equations while simultaneously memorizing a sequence of letters for later recall (Figure 3). The letters served as items to be remembered, and the math problems acted as distractors. During 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

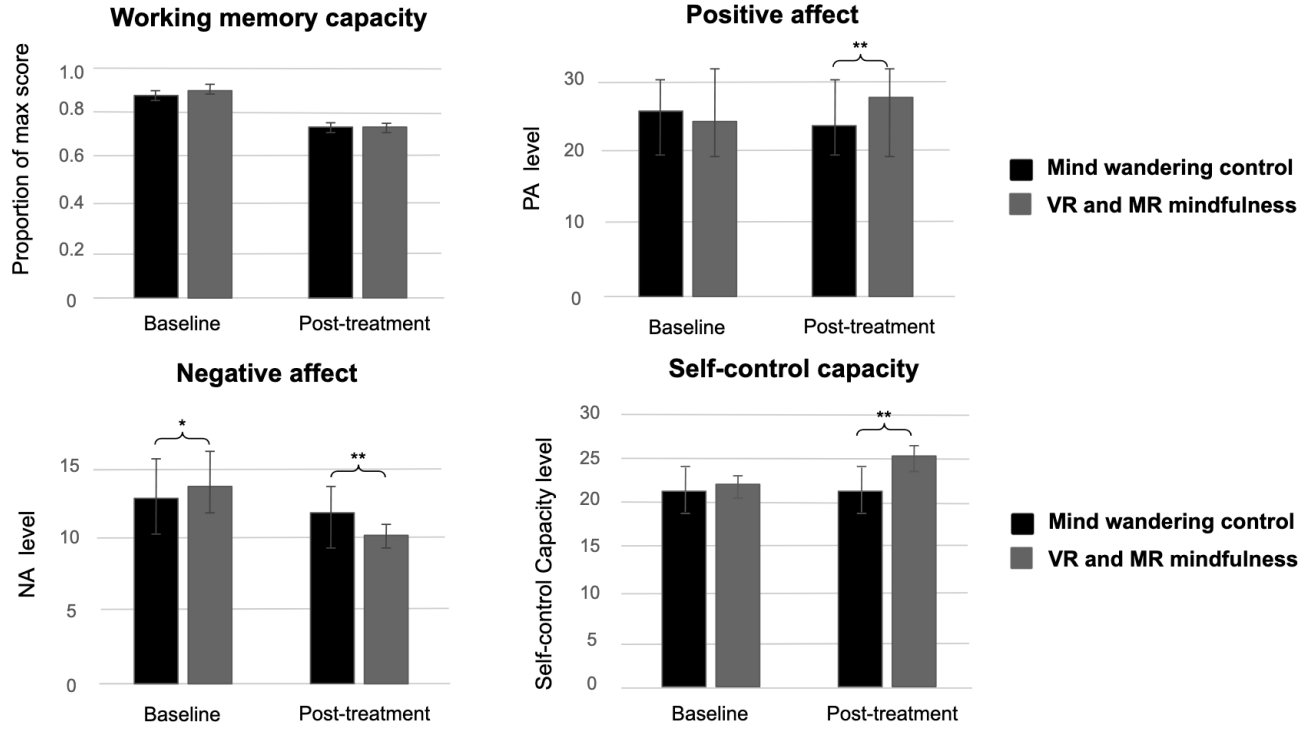
Manipulation Check

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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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.
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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

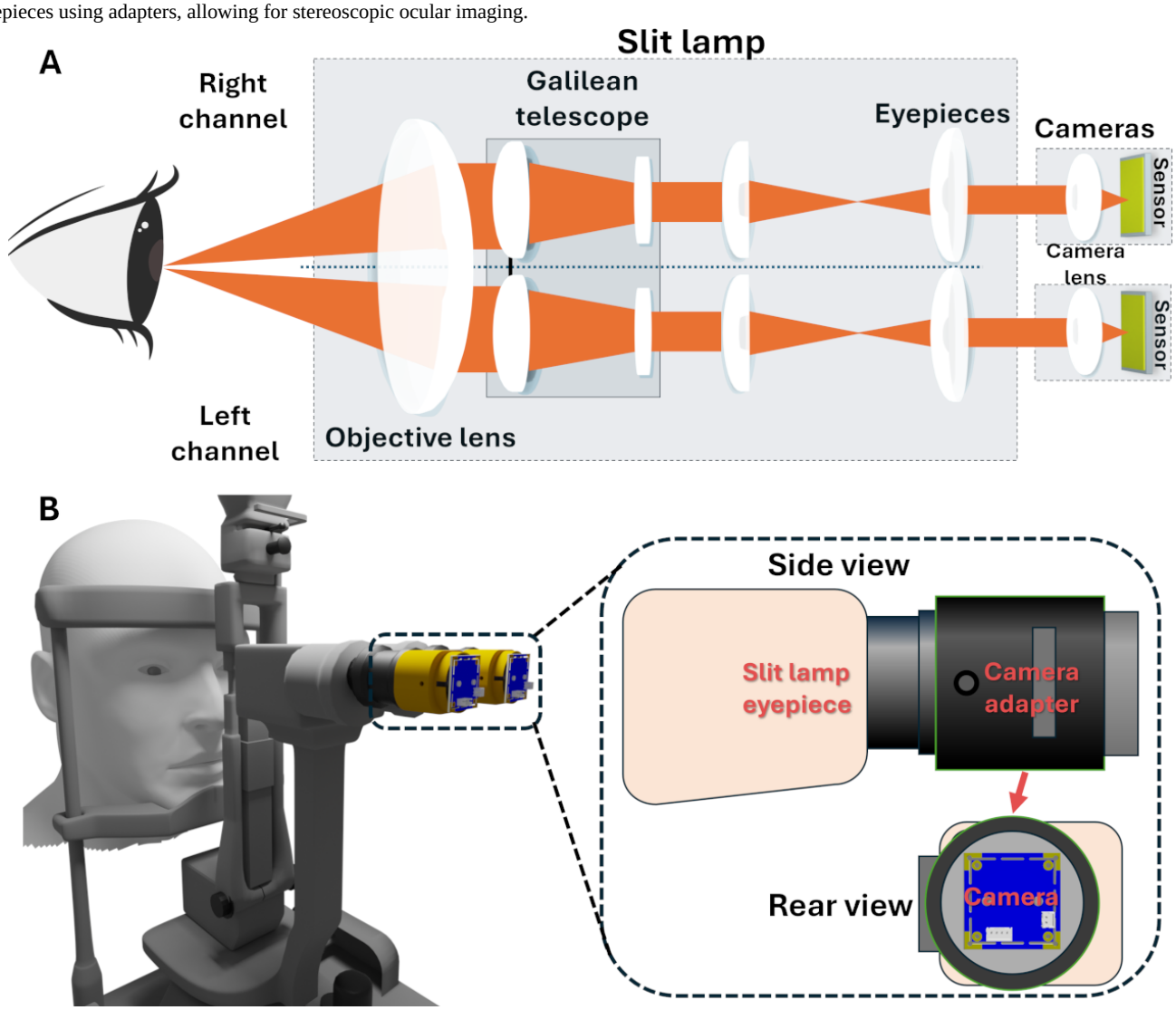
Ethical Considerations

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

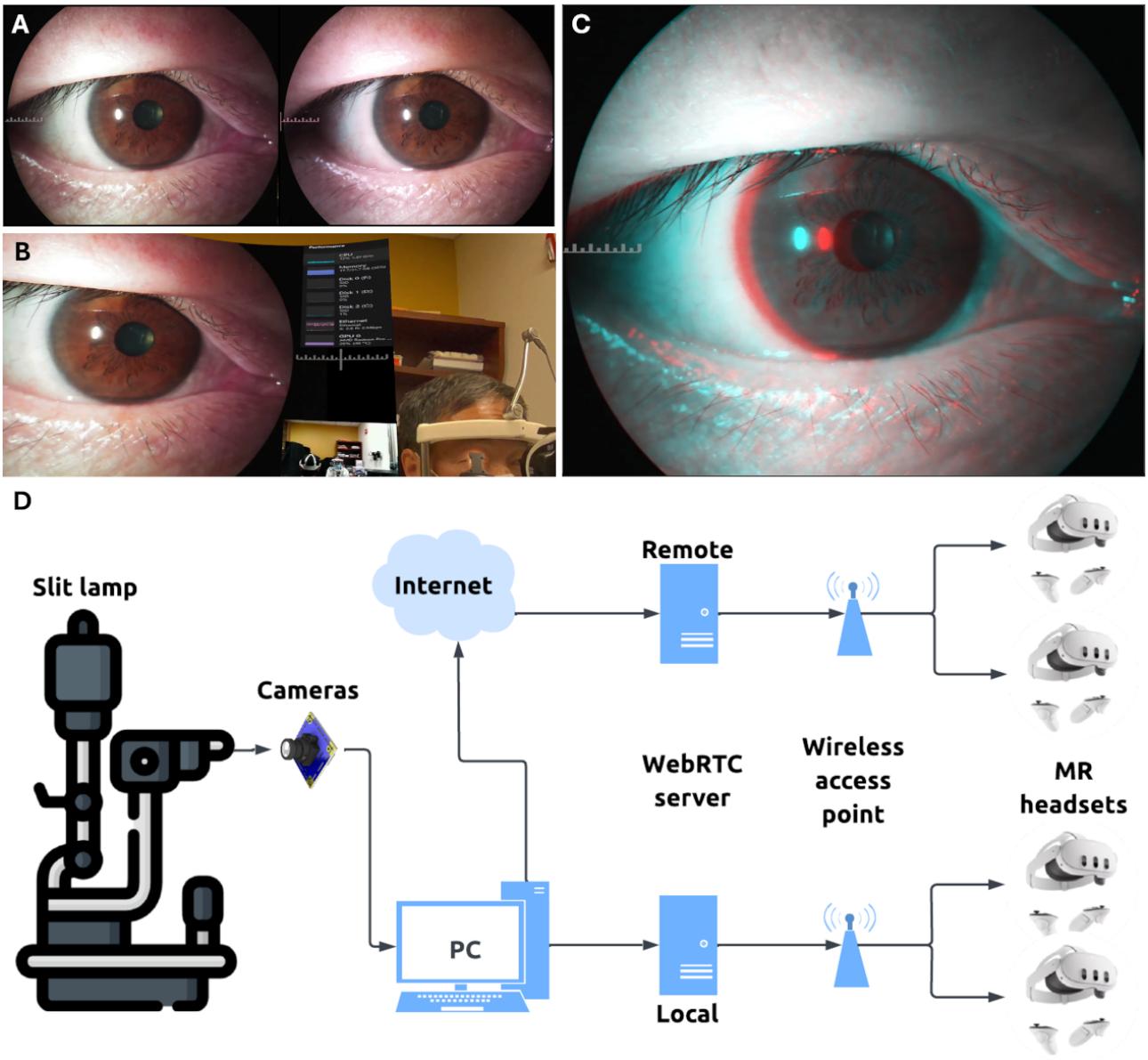
The MR-SLP system developed in this study was built on a commercial slit lamp (XCEL250, Recheit Inc). Two board-level USB video cameras (ELP-USB16MP01-L75, 1/2.8-inch sensor, maximum resolution: 4656×3496 pixels) formed a stereoscopic pair and were calibrated before mounted on the left and right eyepieces 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

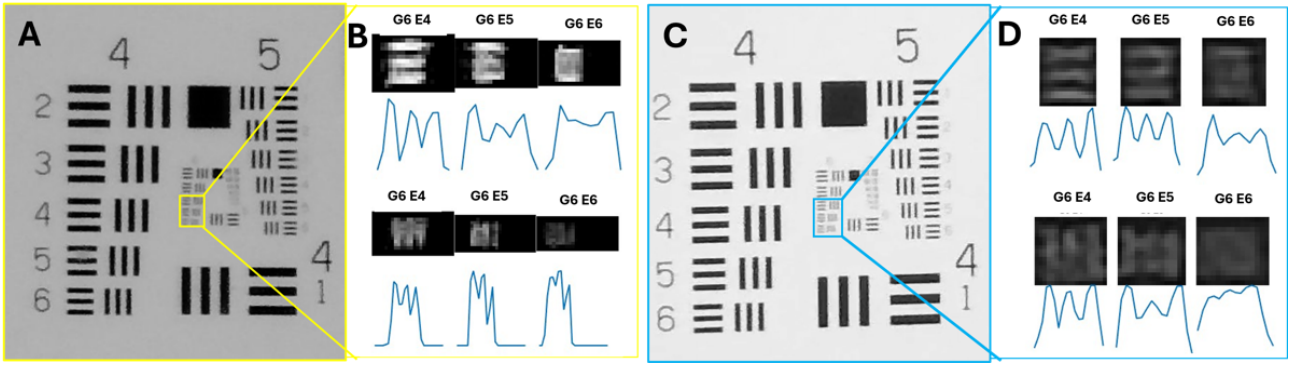
Statistical analyses were performed using R (version 4.5.1; R Foundation for Statistical Computing). The normality of the tube-threading task completion times was assessed using the Shapiro-Wilk test. Given the nonnormal distribution of the data, the nonparametric Kruskal-Wallis test was used to compare 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.

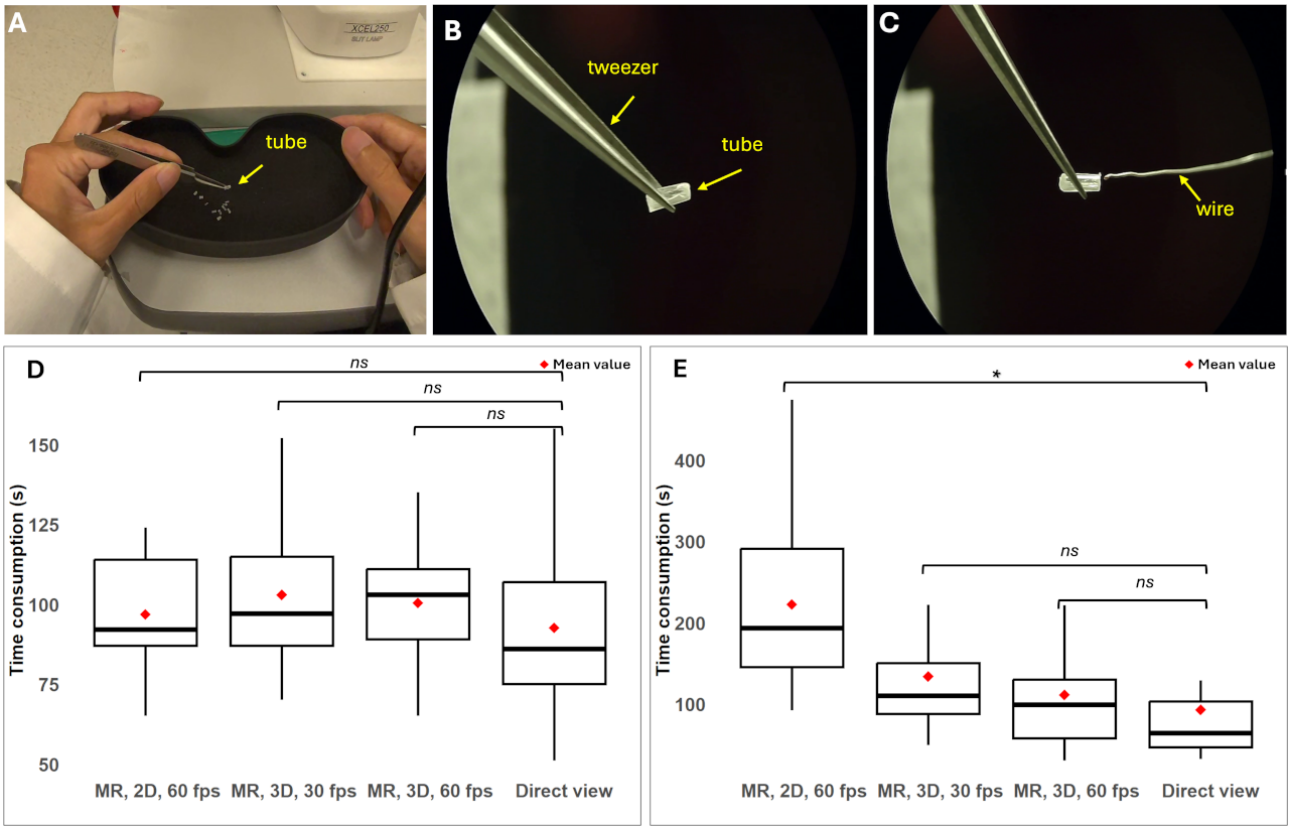


Table . T-task1(p,c) of all participants under all 4 test conditions.[a]

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.

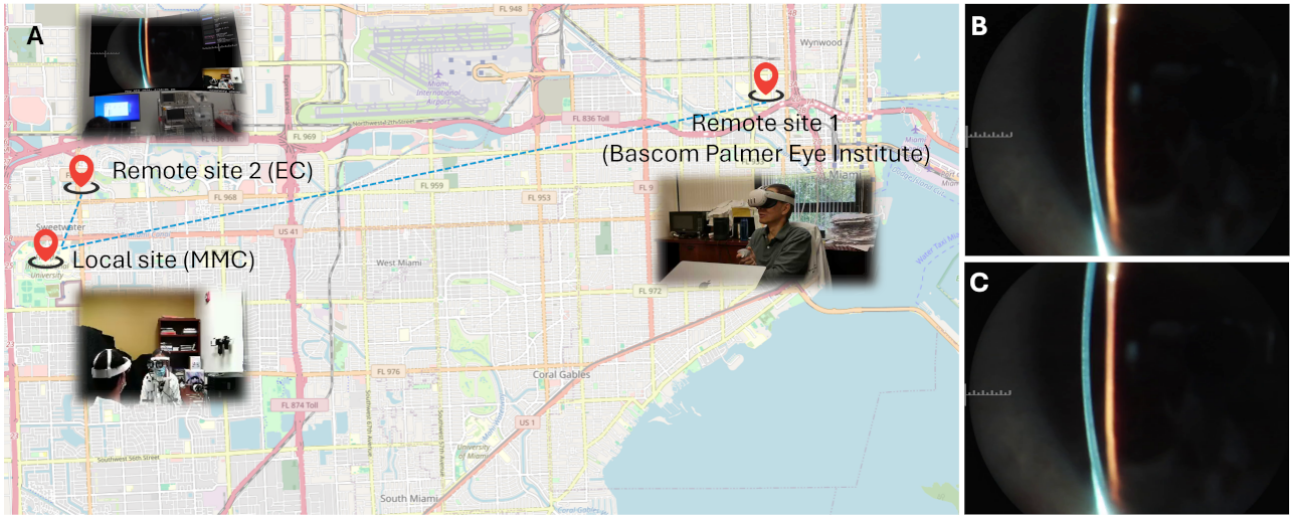
[g]Condition ID 4.

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.

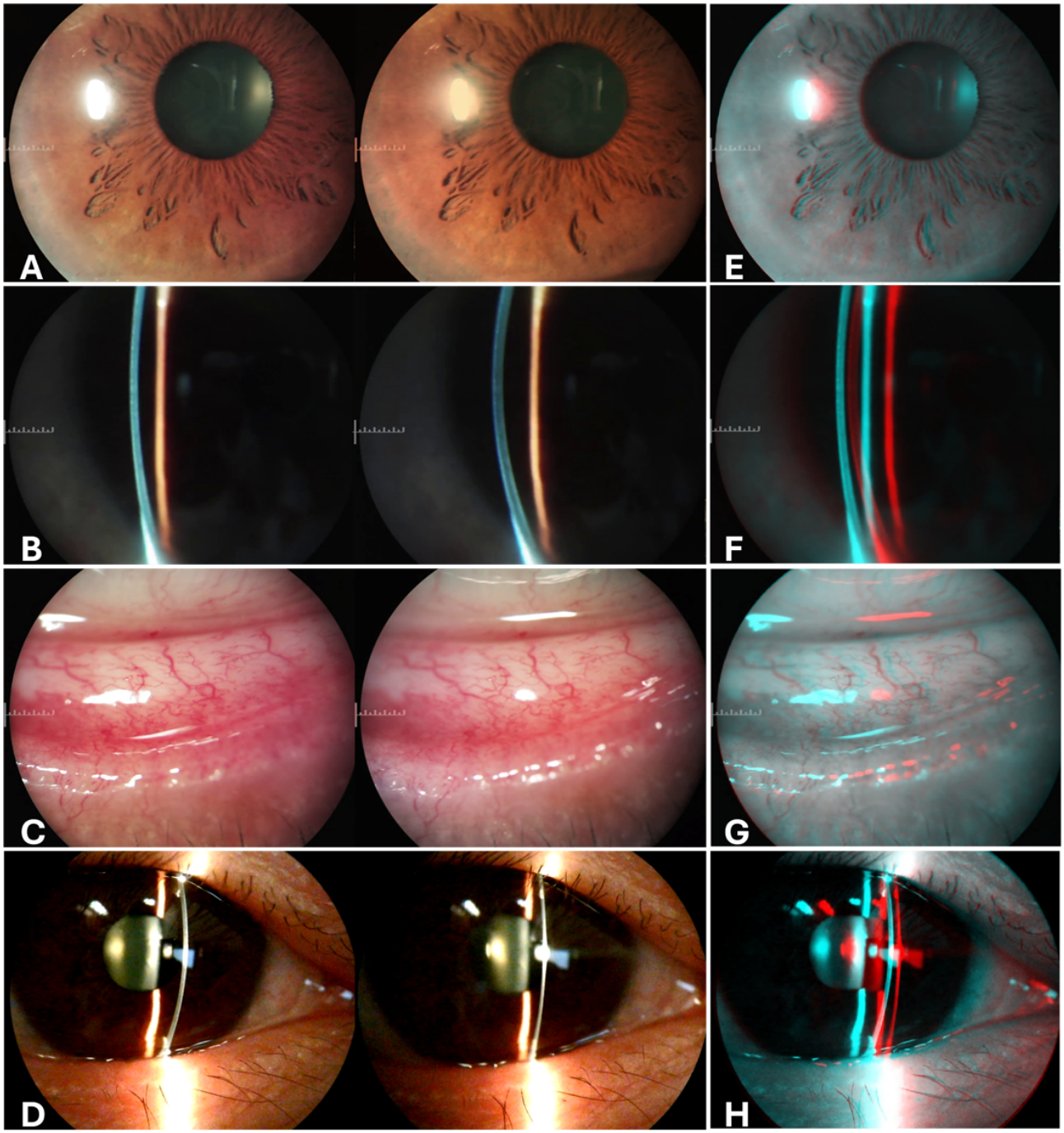
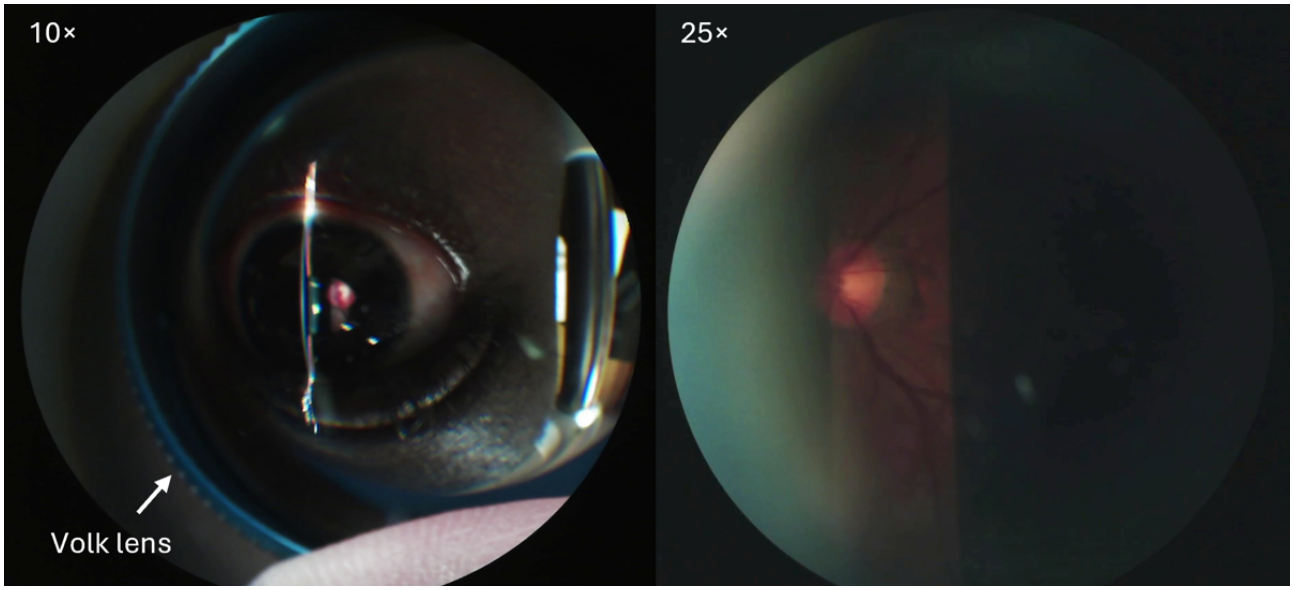


Figure 7. Fundus examination using the mixed reality–based slit lamp. Images were acquired through a handheld 90D Volk lens, showing retinal regions under a nonmydriatic condition at different optical magnifications.



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.

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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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Improving Health-Related Symptoms and Behaviors in Children and Adolescents Diagnosed With Diabetes by Using a Virtual Reality–Gamified Self-Care Method: Randomized Controlled Trial

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Abstract

Background: Self-care plays an important role in improving health symptoms in patients diagnosed with chronic illnesses such as diabetes. Gamification is among the most effective methods for enhancing health monitoring by applying principles of behavioral economics and motivation.

Objective: This study aimed to develop an innovative self-care system using a virtual reality (VR)–gamified intervention and to evaluate its effects on patients diagnosed with diabetes metabolic symptoms and health-related behaviors compared to other standard interventions.

Methods: This study was a randomized controlled trial with a parallel-group design, conducted between December 2024 and February 2025. A total number of 78 patients diagnosed with diabetes were recruited from The Children's Medical Center clinic in a closed, offline setting. Briefing, tutorials, and interventions were partly face-to-face. Eligible participants (n=68) were randomly assigned to the 4 groups using stratified block randomization based on age and sex, with allocation concealment ensured through a sequentially numbered process. Each group received a different type of self-care intervention for 6 weeks, which was health care provider-assisted. One group received the VR gamified intervention, while the other 3 groups received comparator interventions, including the MySugr (mySugr GmbH) monitoring app, traditional counseling, and medication only, respectively. The primary outcomes were fasting blood sugar and health-related behaviors, including physical activity and food intake, while secondary outcomes were long-term metabolic indicators, including hemoglobin A_{1c} (HbA_{1c}) and BMI. All outcomes were measured by self-assessed questionnaires. No blinding was implemented for participants or care providers. However, data analysis was conducted using anonymized group labels. Eight participants were lost to follow-up. Minor missing daily entries were handled by weekly data aggregation.

Results: Data from 60 participants were included in the final analysis (VR-gamified group n=16, application group n=14, counseling group n=15, and control group n=15). Linear mixed model showed significant time×group interaction effects for fasting blood sugar ($F_{15,280}$=2.046; P=.01; partial η^2=.099), physical activity ($F_{15,280.61}$=2.544; P=.001; partial η^2=.120), and food intake ($F_{15,336}$=2.794; P<.001; partial η^2=.111), indicating greater improvement over time in the VR gamification group compared with the other parallel groups. No statistically significant differences were observed for BMI or glycated hemoglobin. No serious adverse events related to the VR intervention were reported.

Conclusions: VR gamified self-care interventions may potentially contribute to better management of diabetes-related symptoms and behaviors compared with conventional self-care approaches. Such gamified VR systems show promise as alternative or complementary tools for enhancing health outcomes among children and adolescents diagnosed with diabetes.

Trial Registration: Iranian Registry of Clinical Trials IRCT 89347; https://www.irct.ir/trial/89347

(JMIR XR Spatial Comput 2026;3:e81402) doi:10.2196/81402

KEYWORDS

diabetes; gamification; health; self-care; virtual reality

Introduction

Background

Self-care plays an important role in managing the progression of chronic diseases. A high level of control and effective symptom management can improve both somatic and psychological well-being in patients [1]. Self-care systems use personal goal-setting, social support, self-monitoring, and education to help patients in their daily lives [2]. Among various self-care approaches, technological methods appear to be more effective than others. The global availability and relatively low cost of technologies such as computers and smartphones make them suitable for remote monitoring and self-management [3].

Diabetes mellitus (DM) is a chronic disease that is directly influenced by lifestyle, including habits and behaviors related to glycemic control, dietary adherence, and physical activity. Therefore, encouraging motivation for self-care is a crucial aspect of diabetes treatment [4]. Poor control of diabetic symptoms can lead to mortality, while increasing physical activity and improving glycemic control can help prevent morbidity [5]. According to the "Association of Diabetes Care and Education Specialists 7" framework, any diabetes self-care approach must have a measurable impact on specific factors. These include a healthy diet, physical activity, medication management, and regular blood glucose monitoring [6].

Studies have demonstrated the relative effectiveness of health monitoring applications in enhancing daily self-care among patients diagnosed with diabetes. Numerous programs utilize health tracking processes in the context of diabetes self-care [2]. Most apps focus on blood glucose monitoring, which has been identified as the most important metric for diabetes management [6]. One well-known example is the Glucose Buddy (Azumio Inc) app, which allows users to manually log and track diabetes-related metrics such as blood glucose levels [7]. Mobile self-monitoring apps should include multiple features, such as blood glucose tracking, physical activity monitoring, food intake logging, reminders, note-taking, and social support, to be fully functional [8]. However, it has been shown that relying solely on self-monitoring features without incorporating gamification can limit the program's effectiveness in improving self-care behaviors [9]. Platforms like SlimKicker (Henley Wing Chiu) are examples of systems designed for tracking health metrics and physical activity without incorporating engaging game design elements [10]. In contrast, MySugr (Roche diabetes care) is a diabetes management app that combines health monitoring with gamification elements to enhance user engagement and adherence [11].

Gamification is the process of using game elements to engage and motivate individuals in serious contexts unrelated to entertainment [10]. Applying gamification in health care is an effective tool for shaping patient behavior through user engagement [12]. Techniques such as self-monitoring, goal setting, reward structures, social incentives, level design, medal/badge systems, and narrative context are among the most well-known and widely used behavior change strategies [13]. Reward and incentive systems have a powerful impact on habit formation and can foster intrinsic motivation for users to repeatedly engage in desired behaviors [14].

It has been shown that gamification is more effective in establishing desirable healthy habits than health monitoring alone [9]. Evidence indicates that gamification in mobile health apps leads to measurable improvements in glycemic control and medication adherence [15]. As an example, the MySugr program allows users to track and monitor their blood glucose levels, medications, and calorie intake while using challenges, achievements, and a monster avatar to encourage regular data logging [14]. Gamification enhances user motivation and supports behavior change by making health-related tasks more enjoyable and goal-oriented [16]. Techniques like point scoring, social incentives, and predictable rewards for desired actions effectively facilitate habit formation and behavioral change by reinforcing target behaviors and shaping lasting routines [17]. One of the most notable examples is exergames, games designed to promote physical activity. Games like Bant (University Health Network) track users' physical activity using GPS and encourage improvement [10]. It has been shown that incorporating scoring and reward systems in exergames can effectively foster sustained physical activity in users [18].

However, sole reliance on points and rewards can undermine the essence of gamification, making the experience less entertaining and engaging. Scoring elements must be integrated into a compelling and enjoyable context [14]. Studies indicate that using narrative and engaging audiovisual designs, similar to features found in video games, can convey a sense of fun, immersion, and pleasure, helping to reduce the perception of pain or discomfort [6]. A major flaw in traditional gamification designs is the absence of essential game elements such as narration, high-quality graphics, and gameplay, resulting in emotionally unappealing experiences for children and adolescents [19]. Integrating visually engaging elements and fun designs helps maintain user interest and enhances the educational value of diabetes self-care apps [20]. By using compulsion loops, cycles involving anticipation of a reward, performing an action, and receiving the reward, gamified systems can reinforce desired behavioral habits [21]. Some studies describe gamification as an art form, emphasizing that the most effective way to foster behavioral change is through well-designed reward systems. Aesthetically appealing and strategically crafted rewards engage both cognitive and motivational systems to shape lasting habits [22].

Apart from using the mentioned game design elements, creating an immersive atmosphere is necessary to reach an engaging experience. Toward this goal, the use of virtual reality (VR) platforms has been increasingly discussed in recent years [23]. Jo and Park [24] found that VR's visual aesthetics, including shape, depth, 3D graphics, and visual design, significantly influence perceived enjoyment and adherence to the technology. VR promotes behavior change through technological novelty focused on embodied experience. By incorporating interactive designs, VR creates a sense of flow, presence, and immersion [25]. Studies show VR environments can encourage healthy behaviors, including regular exercise and proper nutrition [26].

Objectives

The main goal of this research was to design an innovative gamification program for diabetes self-care. To our knowledge, there is limited evidence of gamified VR programs that integrate similar audiovisual and gameplay elements for diabetes self-care. This study helps address this gap by providing an initial implementation and evaluation of such a system. Following the development of the app, the next objective of our research was to assess its effectiveness in improving diabetes symptoms.

To evaluate the efficiency of every self-care method, such as our VR-gamified app, there are some metrics used in previous literature. Blood glucose monitoring is recognized as the most important metric of diabetes self-care [6]. Fasting blood sugar (FBS) is considered a short-term marker of blood glucose levels, while hemoglobin A_{1c} (HbA_{1c}) serves as a long-term indicator [27]. Research has identified several key factors that influence blood glucose control, with dietary adherence and physical activity being among the most significant predictors of glycemic regulation [28]. In line with these findings, we used 5 key metrics to evaluate the effectiveness of our designed intervention. These metrics are categorized into two main groups: (1) health symptoms, including FBS, HbA_{1c}, and BMI, and (2) health-related behaviors, including physical activity and food intake.

We hypothesized that experiencing our VR gamified program would have a greater impact on improving the primary self-care outcomes for diabetes. Based on this expectation, the following 5 hypotheses were formulated:

- Hypothesis 1 (H1): the improvement in the weekly average of FBS over time differs between the VR gamified group and the other experimental groups.
- Hypothesis 2 (H2): the improvement in the weekly total physical activity over time differs between the VR gamified group and the other experimental groups.
- Hypothesis 3 (H3): the improvement in the weekly average of daily food intake over time differs between the VR-gamified group and the other experimental groups.
- Hypothesis 4 (H4): the improvement in the weekly calculated BMI over time differs between the VR-gamified group and the other experimental groups.
- Hypothesis 5 (H5): the change in HbA_{1c} from pretest to posttest observations differs between the VR-gamified group and the other experimental groups.

Methods

Trial Design

The study used a parallel-group randomized controlled trial comprising 4 arms, with participants allocated to the groups with respective sizes of 16, 14, 15, and 15 for final analysis. Each group received one kind of self-care intervention for a 6-week period.

Two methodological changes were implemented after trial commencement. First, the physical activity measurement approach was modified from objective pedometer-based tracking to structured self-report assessment to enhance feasibility and adherence in the clinical setting. Second, the Iranian diabetes-monitoring app Idia (Mehr Nutrition Technology and Knowledge Development) was initially planned as a comparator for the VR-gamified group; however, limitations in its expected feature set necessitated its replacement with the MySugr app as one of the comparators.

Participants

The target population for this study consisted of children and adolescents aged 7-15 years diagnosed with diabetes, living in Tehran, Iran. Inclusion criteria were (1) a formal diagnosis of diabetes, (2) aged between 7 and 15 years, (3) basic computer/VR literacy, and (4) willingness and ability to participate in a 6-week eHealth trial. Exclusion criteria included any medical conditions that would prevent safe use of VR headsets (eg, cybersickness or nausea). The research team was introduced to potential participants as specialists in health psychology affiliated with the PhD program at the University of Tehran in order to provide a clear professional context for the intervention. A total of 78 participants meeting the inclusion criteria were recruited from The Children's Medical Center in August 2024 to November 2024, Tehran, Iran, in an offline, closed manner. Following recruitment, participants were provided with face-to-face instructions and a briefing. Written informed consent was subsequently obtained from eligible participants (n=68) who enrolled in the trial. Eight participants lost to follow-up over the 6-week period, resulting in a final sample of 60 participants (mean age 11.8, SD 1.74 years; 33, 55.0% boys and 27, 45.0% girls). All outcomes were self-assessed by online questionnaires throughout the trial timeline.

Interventions

VR Gamified Group

Participants in this group engaged with the VR gamified program developed specifically for this study.

Participants engaged in one supervised VR gamified session per week for 6 consecutive weeks. Each session lasted approximately 5 - 15 minutes and took place in the clinical setting. In every session, participants played one level of the KalleGhandi (Ruhollah Solat) VR game, with the difficulty adjusted based on their weekly glycemic and behavioral data obtained prior to the session. Two care providers, including one health professional and one technical assistant, were present to provide onboarding, headset setup, and technical support throughout the intervention. Participants accessed the VR game at the medical clinic following their weekly physician visit. No payment was required from participants. The game was experienced using a VR headset provided by the university, and participants did not have personal access to the device outside the clinical setting. No prompts were used, but weekly Telegram (Telegram Messenger LLP) messages were sent to participants to remind them about the intervention and related self-assessments. Apart from slight differences in the level of training, no co-intervention was provided during the trial.

The VR game used in this study (see Figure 1) was designed and developed by the first author (RS). With part-time support

from a technical game development team in Iran, the product was developed and finalized through several iterative phases between November 2023 and October 2024, using the Unity engine (version 2022.3.44f1; Unity Technologies) and tested on the Oculus Meta Quest 2 (Meta Platforms) VR headset. Figure 2 shows one screenshot of the process of making the game in the Unity engine. For ensuring quality assurance and taking feedback about the experience, the game was pilot-tested multiple times with participants without diabetes prior to the main study. The game was designed in the first-person shooter genre. In the first core mechanic of the game, players use their VR right-hand controller to shoot enemies represented as unhealthy food items such as ice cream, pizza, and cheese. The second core mechanic involves using an insulin pen with the VR left-hand controller to break down and collect sugar cubes scattered throughout the environment. Each session lasts 5 minutes, and based on the number of sugar cubes collected, participants are awarded a medal: gold, silver, or bronze.

Figure 1. Visual overview of the "KalleGhandi" virtual reality gamification program used as an intervention in this randomized controlled trial study.

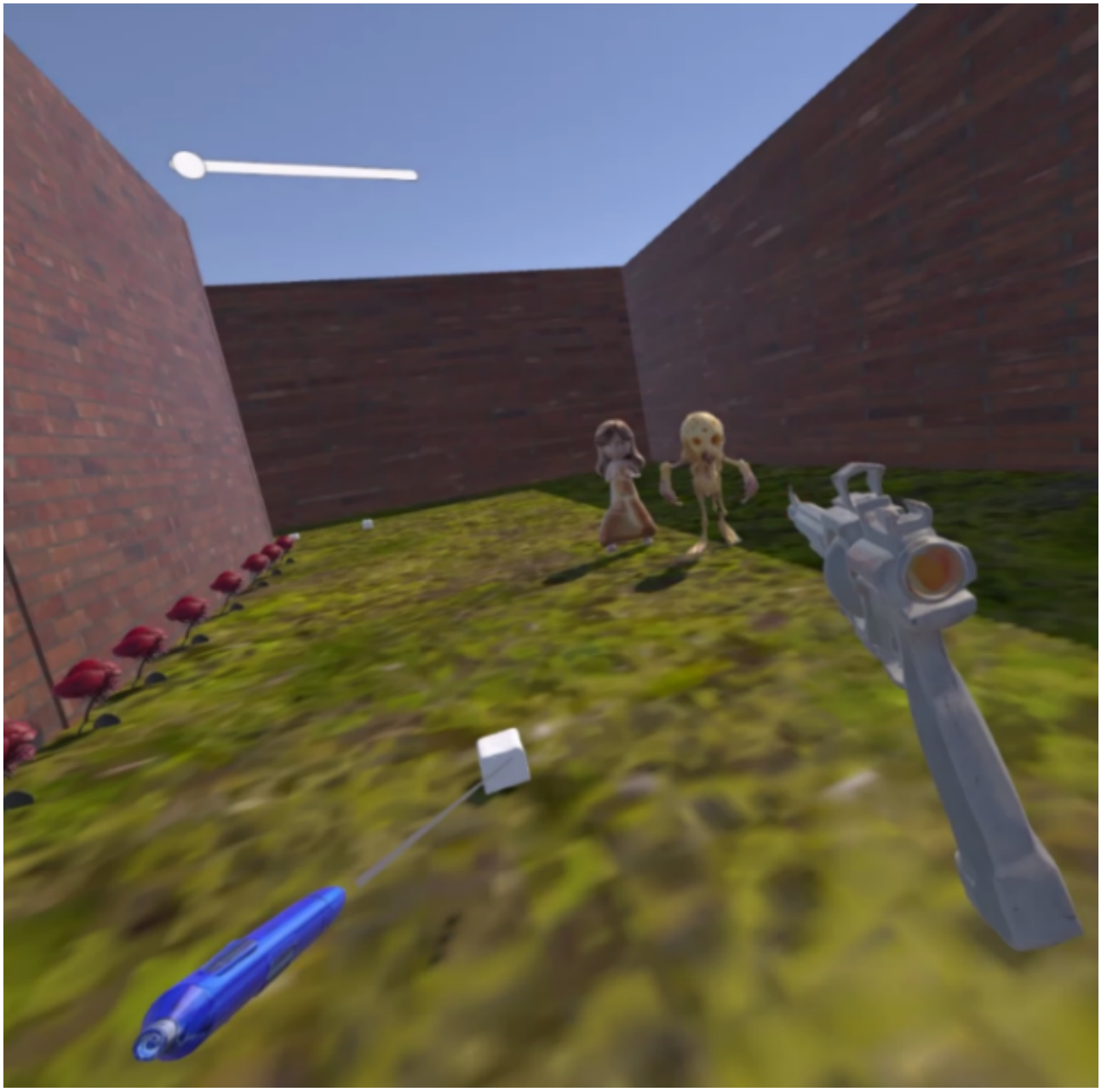
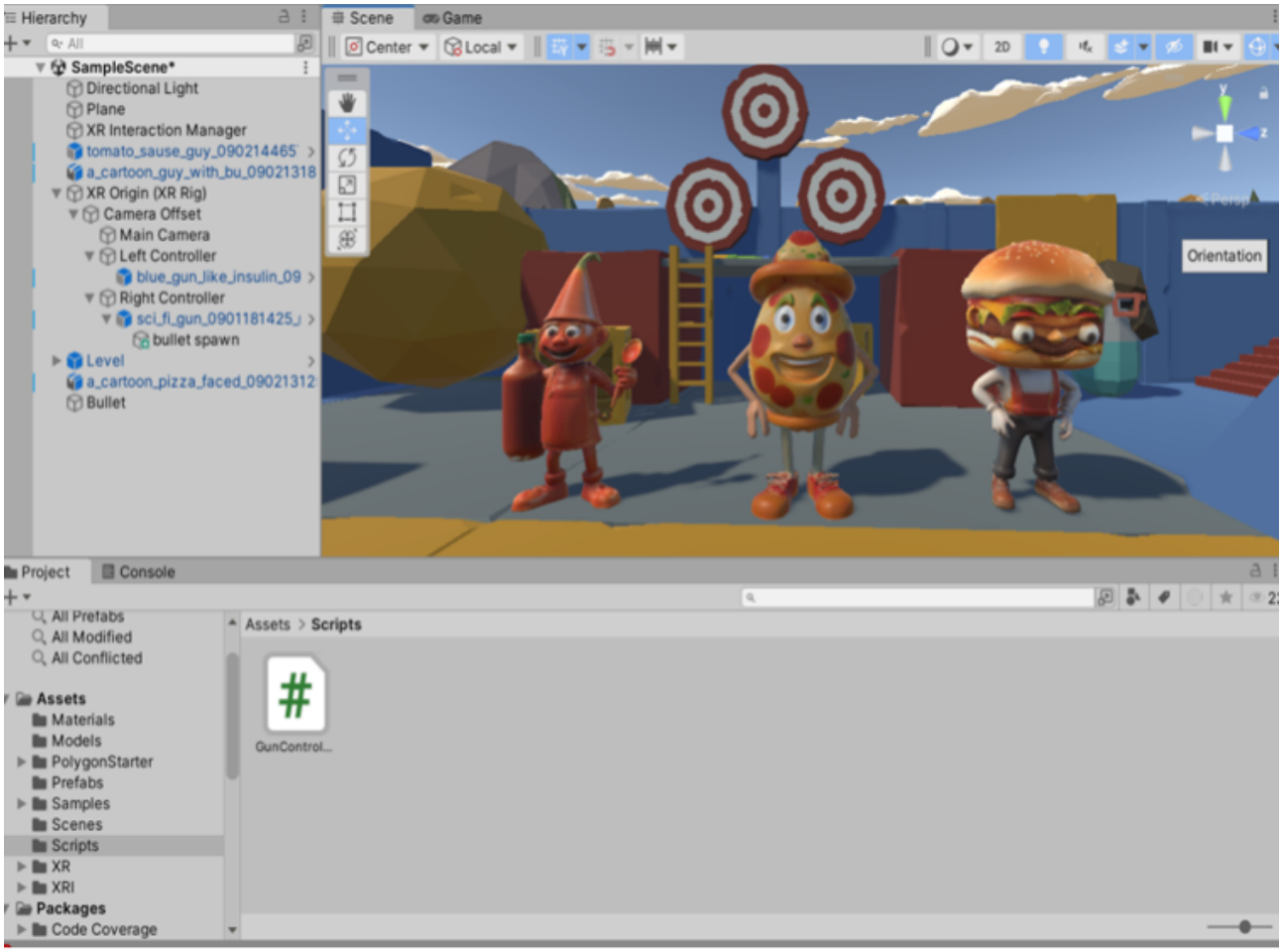


Figure 2. A screenshot taken from the process of making the game "KalleGhandi." Unity 2022.3.44fl game engine.



The gamification design links each gameplay element directly to real-life diabetes management behaviors. Specifically, the target number of sugar cubes is dynamically set based on the participant's weekly average FBS. Lower FBS averages reduce the target, making it easier to earn medals, while higher FBS averages increase the difficulty. Similarly, the player's movement speed in the game is determined by their physical activity level, and the number of enemies (unhealthy foods) is determined by the weekly average food calories. This integration of real-life health indicators into gameplay is intended to reinforce positive self-care behaviors.

To facilitate accessibility and ensure replicability, the source codes of the KalleGhandi game are provided in Multimedia Appendix 1, while 2 versions of the game have been uploaded to the Open Science Framework (OSF):

- The Windows build (for playing on a PC with a VR headset connection) is available [29].
- The Android build (for stand-alone headset use) is available [30].

Usability and Tolerability Assessment

Throughout the VR intervention, participants and caregivers were monitored for usability issues, cybersickness, or discomfort. Tolerability indicators (nausea, dizziness, and visual fatigue) were recorded via caregiver observations at each session. No adverse events or dropouts due to VR intolerance occurred. All sessions were conducted under adult supervision, with optional rest breaks. In addition to observational monitoring, participants completed standardized measures to capture their subjective experience of ease of use, perceived usefulness, and overall interaction quality with the VR system. System usability was measured using the System Usability Scale developed by Brooke [31], which consists of 10 items rated on a 5-point Likert scale. Technology acceptance was measured based on the Technology Acceptance Model (TAM) construct developed by Davis [32]. The TAM model's core constructs, perceived usefulness, and perceived ease of use were operationalized to assess users' perception of extended reality (XR) technology. After experiencing 6 consecutive sessions, participants completed the Persian-translated versions of both questionnaires to ensure clarity and language accessibility for children and adolescent participants.

Application Group

Participants in this group used the commercially available diabetes self-care app MySugr (Android/iOS, standard free version available during the study period 2024 - 2025) as a comparator to the VR gamified intervention.

At baseline, participants received a brief, structured training session (approximately 20 - 30 min) on how to:

- Create a personal user account and log in to the app;
- Log their blood glucose measurements obtained from their home glucometer;

- Record their dietary intake and approximate calorie consumption; and
- Review the summary feedback provided by the app.

Participants used the MySugr app to log and self-monitor their blood glucose values and dietary intake. They received automated reminders prompting them to record glucose measurements and diet-related information. Participants also interacted with the app's gamified "monster" avatar, which responded to completed logging tasks by providing visual feedback and rewards; this feature constituted the primary gamification component of the intervention.

Participants were instructed to use the app between 2 and 5 times per day, typically for several minutes per session, to enter their fasting and postprandial blood glucose values and main meals. App usage (frequency and duration) was based on self-report during follow-up visits/phone calls rather than backend log data, as we did not have access to the app's internal usage analytics.

Traditional Counseling Group

This group received diabetes self-care counseling provided by professional diabetes consultancy centers in Iran.

Participants were already enrolled in diabetes care programs at either Gabric Institute or the Iranian Diabetes Center, where they routinely received counseling and self-care support alongside medication services. Counseling interactions typically occurred multiple times per week via Telegram channels and phone calls. Each participant had a primary counselor familiar with their case and family, offering tailored guidance for diabetes self-care. Institutional practices are largely uniform but not scripted.

Control Group

Participants in this group received medical care by an endocrinology/child-adolescent diabetes/nutrition specialist on a weekly or monthly basis but did not receive any additional psychological health-related self-care intervention.

Outcomes

All participants (or their parents) were instructed to complete a structured data collection form throughout the 6-week study period, which is provided in Multimedia Appendix 2. The form required daily entries, including FBS, food intake, and physical activity, along with weekly entries for body weight. HbA_{1c} levels were recorded twice, once at baseline (pretest) and once after the final session (posttest). Demographic variables, including age, gender, and type of diabetes, were collected at the outset.

Primary Outcomes

Weekly Average Daily Monitored FBS

Participants measured their FBS levels every morning using a personal glucometer and self-reported the values. The recorded daily FBS values were then used by the experimenters to calculate a weekly average for each participant.

FBS values were measured by participants using personal home glucometers commonly available in community pharmacies. Because measurements were conducted in real-world settings, different commercially available glucometer brands like Accu-Check were used. Participants were instructed to measure blood glucose in the morning after an overnight fast (at least 8 h) following standard self-monitoring procedures recommended for home glucose testing. No continuous glucose monitoring devices were used in this study. Daily FBS values were recorded by participants and submitted through the study reporting forms.

Weekly Sum of Daily Calculated Physical Activity

Physical activity was quantified using a bar metric; one bar equaled either 30 minutes of vigorous activity (eg, gym workouts or swimming) or 60 minutes of moderate activity (eg, jogging). The weekly sum was calculated based on this definition.

As the study prioritized pragmatic feasibility in real-world settings, we intentionally relied on structured self-report measures rather than resource-intensive objective tools such as pedometers to record daily physical activity. Participants and parents received brief standardized training on reporting physical activity using the bar metric with examples of common daily exercises. This change in measurement methods happened shortly after the commencement of the trial.

Weekly Average Daily Calculated Food Intake

Participants either reported their total daily caloric intake directly or reported their food descriptions, from which caloric values were estimated. A weekly average of daily caloric intake was then computed.

To preserve pragmatic feasibility and participants' adherence, dietary intake was assessed using a self-assessment approach, rather than resource-intensive objective methods. Participants and parents received brief standardized training on estimating daily caloric intake using a nationally recognized Iranian food-calorie database (Dr Kermani's online nutrition resource [33]). Although self-report measures are inherently vulnerable to reporting bias, self-assessment contributed to operational feasibility, participant adherence, and real-world generalizability of the findings.

Secondary Outcomes

Weekly Calculated BMI

Participants self-reported their weight on a weekly basis. BMI was calculated using the standard formula: weight (kg) divided by height squared (m^2), which had been reported at first.

HbA_{1c} Pretest and Posttest

HbA_{1c} levels were measured twice via laboratory blood tests, once before the intervention (pretest) and once at the conclusion of the study (posttest), serving as a long-term indicator of blood glucose control.

Participants were instructed to undergo HbA_{1c} testing at a certified clinical laboratory of their choice using standard methods routinely used in clinical practice (eg, high-performance liquid chromatography or equivalent). All laboratories were accredited according to national standards. As HbA_{1c} measurements were collected from multiple

laboratories, the same laboratory was not used for all participants; however, HbA_{1c} is a standardized biomarker with minimal interlaboratory variability.

Sample Size

Sample size was calculated using G*Power (Heinrich Heine University Düsseldorf) software based on a repeated-measures ANOVA design with 4 groups. Assuming a medium effect size (f=.25), a significance level of α=.05, and statistical power of 0.80, the minimum required total sample size was estimated to be 52 participants. To account for potential attrition, additional participants were recruited. No interim analyses or stopping guidelines were defined or conducted.

Randomization

Participants were randomly assigned to one of the 4 groups using computer-generated stratified block randomization based on age and sex. The allocation sequence was generated by the technical assistant who was not involved in the study assessments. Allocation concealment was maintained through a sequentially numbered process, and the care provider responsible for briefing and tutorials remained unaware of group assignments until the moment of allocation.

Blinding

Due to the nature of the interventions, neither participants nor care providers could be blinded to group assignments. All outcome data were self-reported via online questionnaires, with no external outcome assessor involved. However, the data analyst was provided with anonymized group labels to minimize potential analysis bias. To reduce preconceived biases about the intervention of interest and comparators**,** the informed consent focused on the shared goal of diabetes improvement and participants' compensation, ensuring a neutral presentation of all study arms. No similarity of a placebo intervention was applicable here.

Statistical Methods

Given the repeated measurements of outcomes, a linear mixed model (LMM) was used. To investigate significant differences between groups, one-way ANOVA and paired-samples 2-tailed t tests were used. A correlation analysis was also used as an additional analysis. All statistical analyses were performed using SPSS Statistics (version 27; IBM Corp). The significance level was set at α=.05 for all statistical tests.

Handling of missing data: the variables BMI and HbA_{1c} contained no missing data, as BMI was derived from weekly weight measurements and HbA_{1c} was collected only at the pretest and posttest time points. The other 3 outcomes were constructed at the weekly level, as it is an established, accepted practice in mobile health and diabetes care studies. For FBS, physical activity, and food intake**,** missing values existed only in the daily records. According to the operational definitions of the study, these variables were aggregated to the weekly level using the mean or sum of the available daily entries. Weeks with partial daily logs were still computable, because weekly values can be calculated based on the days that were present rather than requiring a complete daily set. As a result of this aggregation process, the final analytic dataset contained no missing values for any of the weekly variables. No imputation procedure was used.

Reporting Guideline

The study was reported in accordance with the CONSORT (Consolidated Standards of Reporting Trials) 2010 statement. The preparation of the manuscript followed the CONSORT-EHEALTH (Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth) reporting framework (Checklist 1) [34], and the abstract was structured according to the CONSORT guidance for abstracts [35], to ensure transparent and standardized reporting.

Ethical Considerations

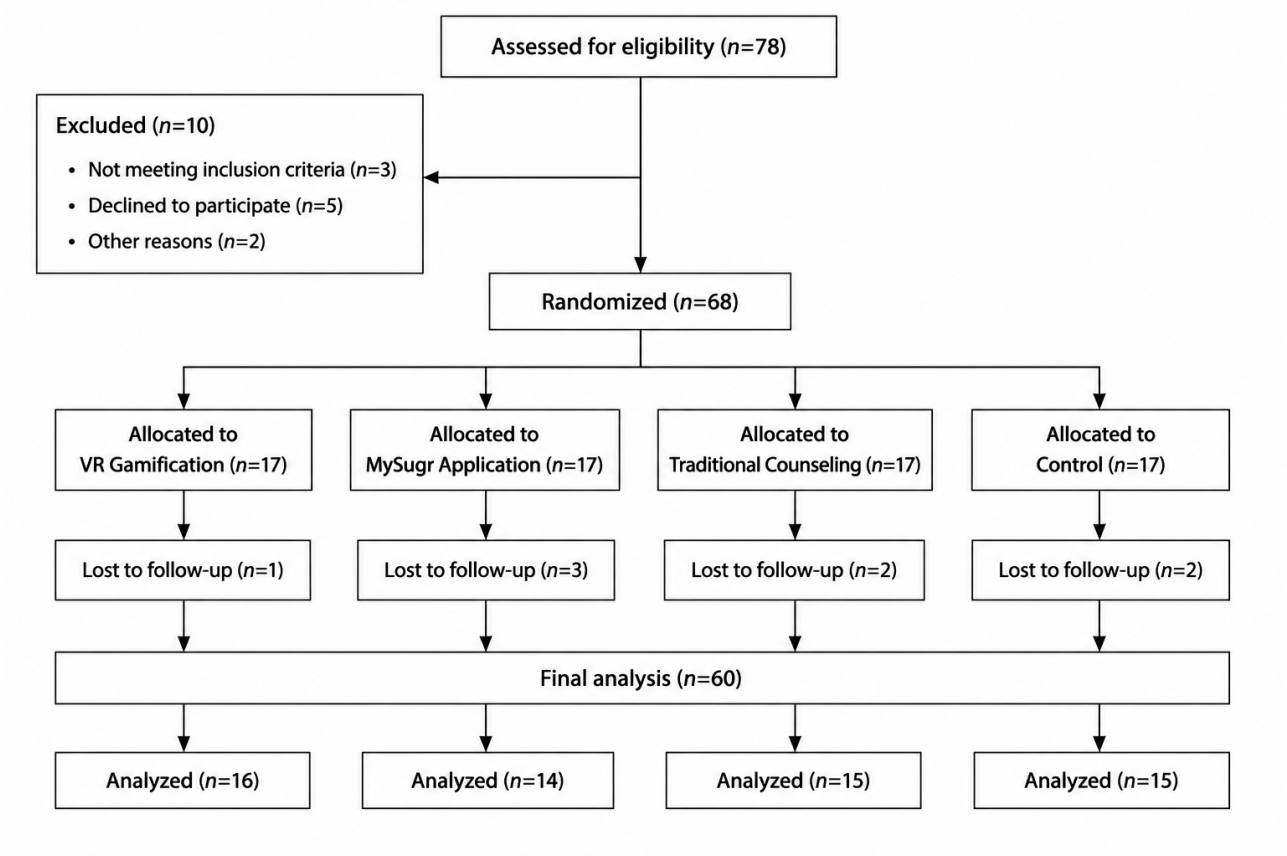
Ethical approval was obtained from the ethical committee of Tehran University's psychology department, under the supervision of the Ministry of Health and Medical Education (MOHME), indexed as IR.UT.PSYEDU.REC.1404.106. All procedures were conducted in accordance with the ethical standards of the institutional research committee and the Declaration of Helsinki. Prior to participation, offline written informed consent was obtained from all participants or their parents. Participants were informed about the purpose of the study, trial procedures, and their right to withdraw at any time without any consequences. Participant privacy and confidentiality were strictly protected throughout the study. All collected data were deidentified and stored using coded identifiers, and no personally identifiable information was included in the analysis or reporting of the results. Access to the data was restricted to the research team and maintained in secure files in accordance with institutional ethical guidelines. No identification of individual participants in any image of the manuscript or supplementary material is possible. Participants received a small compensation to acknowledge the time and effort required to take part in the study. The type and amount of compensation were determined in accordance with the institutional ethical guidelines and were provided equally to all participants regardless of group allocation or study outcomes. No personal or health-related information was collected or transmitted through the VR application. In addition, XR safety procedures were implemented, including supervised use and monitoring for symptoms such as cybersickness, nausea, or any other bodily discomfort.

Results

Participant Flow

A total of 78 individuals were recruited and assessed for eligibility. After the initial briefing**,** 10 were excluded (3 did not fully meet the inclusion criteria, 5 declined to participate, and 2 for other reasons). A total of 68 participants were randomized using stratified block randomization into 4 parallel groups with equal-sized arms (n=17). During the 6-week study period, a total of 8 participants were lost to follow-up. Consequently, 60 participants were included in the final analysis. The detailed participant flow is illustrated in Figure 3.

Figure 3. Participant flow diagram of randomized controlled trial (RCT) program: "Improving diabetes health symptoms by using a specialized VR gamification self-care method: A parallel-group randomized controlled trial" according to CONSORT (Consolidated Standards of Reporting Trials) 2025. Eligibility assessment, enrollment, random allocation, follow-up status, and number of participants analyzed in each group. The study recruited children and adolescents diagnosed with diabetes in Tehran, Iran, from August 2024 to November 2024 and was conducted in December 2024-February 2025.



Recruitment

Participants were recruited and enrolled between August and November 2024. The intervention phase of the trial was conducted from December 2024 to February 2025, during which each participant completed a 6-week follow-up period. The trial concluded as planned without early termination.

Baseline Data

Table 1 presents the baseline demographic and clinical characteristics of participants in the 4 study groups prior to the intervention.

Table . Baseline characteristics of participants in each group. Baseline comparability can be interpreted. Gender is coded as 1=male and 2=female.

Characteristic	VR gamification (n=16)	MySugr app (n=14)	Traditional counseling (n=15)	Control (n=15)
Age (years)				
Mean (SD)	11.75 (2.05)	11.86 (1.66)	11.80 (1.74)	11.60 (1.84)
Range	7 - 15	9 - 15	9 - 15	8 - 15
Gender, mean (SD)	1.44 (0.51)	1.43 (0.51)	1.47 (0.52)	1.47 (0.52)
Diabetes type, mean (SD)	1.25 (0.44)	1.28 (0.46)	1.26 (0.45)	1.26 (0.45)
BMI (kg/m^2)				
Mean (SD)	23.85 (5.55)	24.26 (6.62)	24.47 (6.74)	23.94 (6.18)
Range	18.3 - 36.2	16.2 - 36.2	16.5 - 35.3	18.8 - 37.1
FBS[a] (mg/dL)				
Mean (SD)	123.63 (18.95)	121.14 (18.19)	119.27 (20.22)	119.33 (18.23)
Range	93 - 163	83 - 155	81 - 158	84 - 152
HbA_{1c}[b] (%)				
Mean (SD)	7.94 (0.79)	7.66 (0.89)	8.13 (1.10)	7.51 (0.77)
Range	6.5 - 9.4	6.7 - 9.6	6.5 - 10.2	6.2 - 8.6

[a]FBS: fasting blood sugar.

[b]HbA_{1c}: glycated hemoglobin.

Numbers Analyzed

Data from 60 participants with complete outcome data were included in the final analysis. The denominator for all analyses corresponds to participants who completed the study and provided postintervention measurements. Analyses were conducted according to the originally assigned groups. The analyzed sample sizes were 16 in the VR gamified group, 14 in the MySugr app group, 15 in the traditional counseling group, and 15 in the control group.

Outcomes

The results of the LMM for all 5 outcomes are summarized in Table 2.

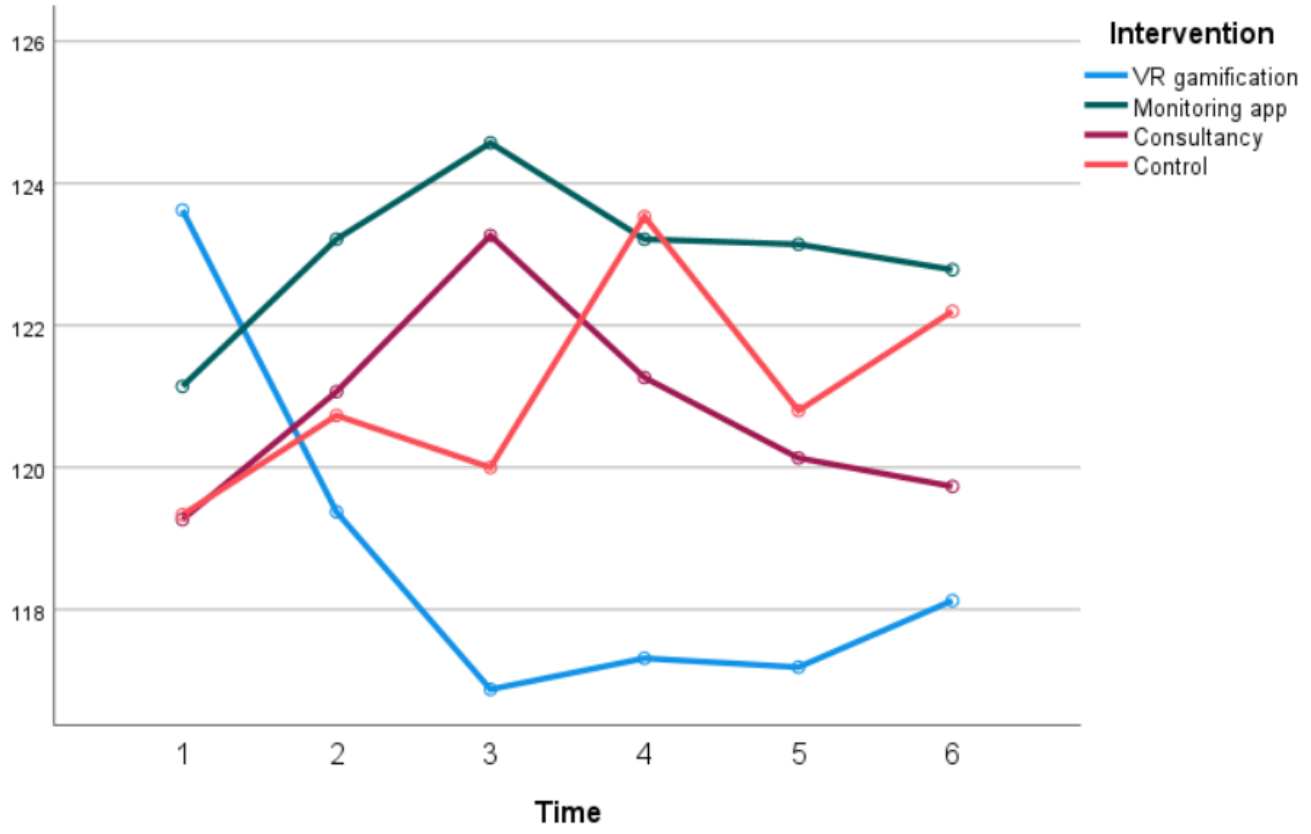
Table . Linear mixed model (LMM) results for trial outcomes. Model fit indices the Akaike information criterion (AIC), residual variance, and fixed-effects tests for time, condition, and their interaction are reported for all outcomes (fasting blood sugar [FBS], physical activity, food intake, BMI, and hemoglobin A_{1c} [HbA_{1c}]) in the parallel-group randomized controlled trial (RCT) evaluating a specialized virtual reality (VR)–gamification self-care program for children and adolescents diagnosed with diabetes. *P* values and effect sizes are reported, respectively.

Outcome and source	*F* (df)	*P* value	Partial η^2	Model fit (AIC)	Residual variance
FBS				2383.29	29.05 (2.45)
Time	0.269 (5,280)	.93	.005		
Time×condition	2.046 (15,280)	.01	.099		
Condition	0.171 (3,39.91)	.91	.001		
Physical activity				1089.44	0.97 (0.08)
Time	1.580 (5,280.61)	.16	.027		
Time×condition	2.544 (15,280.61)	.003	.120		
Condition	14.399 (3.55.96)	<.001	.430		
Food intake				4138.80	4737.43 (400.39)
Time	3.487 (5,336)	.004	.059		
Time×condition	2.794 (15,336)	<.001	.111		
Condition	0.115 (3.336)	.95	.001		
BMI				429.61	0.03 (0.01)
Time	0.602 (5,280)	.69	.011		
Time×condition	0.660 (6.876,128.318)	.70	—		
Condition	0.021 (3,40.19)	.99	.034		
HbA_{1c}				306.57	0.71 (0.09)
Time	0.23 (1,112)	.63	.002		
Time×condition	0.064 (3,112)	.97	.002		
Condition	2.980 (3,112)	.03	.074		

FBS

An LMM was fitted with time, condition**,** and their interaction as fixed effects and a random intercept with autoregressive correlation of order 1 (AR1) covariance for participants. Model fit indices indicated adequate performance (Akaike information criterion [AIC]=2383.29), suggesting that adding time and the interaction improved overall model parsimony relative to the reduced model. The results of the LMM, as reported in Table 2, indicate that the time×condition interaction effect was statistically significant ($F_{15,280}$= 2.046; *P*=.01; partial η^2≈.099). However, no significant main effects were observed for time ($F_{5,280}$=0.269*;* *P*=.93; partial η^2≈.005) or condition ($F_{3,39.91}$=0.171; *P*=.91; partial η^2=.001), suggesting that overall changes over time and between-group differences were not statistically significant in isolation. Random-effects estimates indicated substantial between-subject variability (random-intercept variance=143.45, SE 29.92). The AR1 correlation parameter was negative (ρ=−.19), indicating weak inverse correlation between adjacent repeated measurements. Residual variance was 29.05 (SE 2.45). The temporal changes in the weekly average of FBS across the 4 experimental groups over 6 repeated measurements are illustrated in Figure 4. The significant interaction effect indicates that the pattern of FBS improvement over time varied by group. Specifically, participants in the VR gamified group showed a distinct trend in reducing FBS compared to other groups, with estimated marginal means decreasing from 123.625 mg/dL, 95% CI 114.147-133.103 at baseline to 118.125 mg/dL, 95% CI 110.387-125.863 at week 6. A paired-samples *t* test was conducted to examine the change in average FBS levels within the VR gamified group between the first and last sessions. The results revealed a significant decrease in FBS levels over time (t_{15}=−2.612; *P*=.02; mean difference=−5.500, 95% CI −1.012 to −9.987; Cohen *d*=0.653, 95% CI 0.102-1.186), indicating improved glycemic control among participants in this group, which is in line with recent studies [36]. This finding supports hypothesis 1.

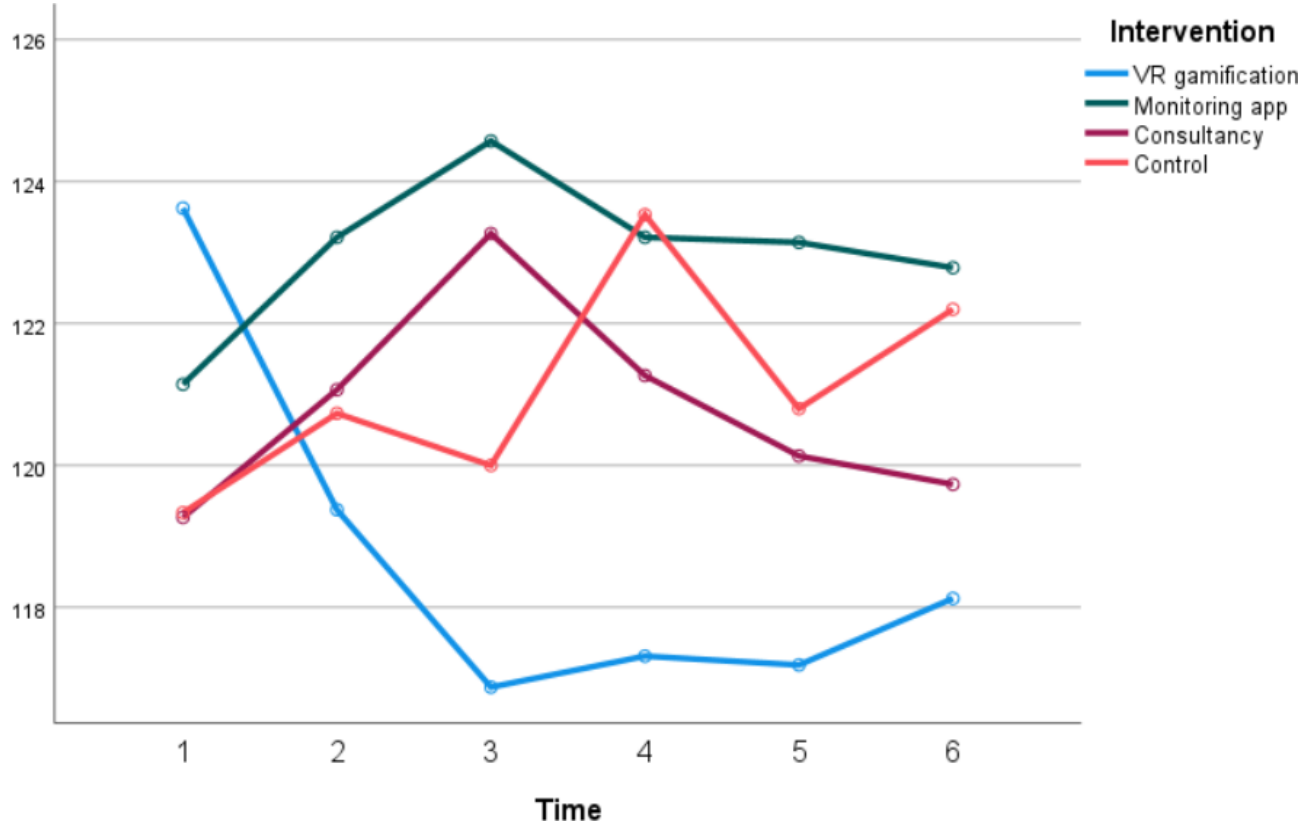
Figure 4. Changes in fasting blood sugar (FBS) over time across intervention conditions. Trajectories show mean FBS values at 6 measurement points for the VR-Gamification, MySugr app, traditional counseling, and control group in the present randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024 to February 2025. VR: virtual reality.



Physical Activity

An LMM was estimated with time**,** condition, and their interaction as fixed effects and a random intercept with an AR1 covariance structure for participants. Model fit indices (AIC=1089.44) indicated a relatively well-fitting model with adequate parsimony for the repeated-measures structure. According to Table 2, LMM results revealed a significant main effect of condition ($F_{3,55.96}$=14.399; P<.001; partial η^2≈.435) and a nonsignificant main effect of time ($F_{5,280.61}$=1.580; P=.16; partial η^2≈.027). The interaction effect of time×condition was significant ($F_{15,280.61}$= 2.544; P=.001; partial η^2≈.120), indicating that changes in physical activity over time differed significantly between the VR gamified group and the other experimental groups. Random-effects estimates showed modest between-subject variability (random-intercept variance=0.155; SE 0.0678). The AR1 correlation parameter was positive (ρ=0.656), indicating moderate positive correlation between adjacent repeated measurements. Residual variance was 0.979 (SE 0.083). Figure 5 illustrates the temporal changes in weekly physical activity across the 4 experimental groups. While physical activity levels remained relatively stable in the control, traditional, and app-based groups, the VR gamified group exhibited a noticeable upward trend over time. Thus, hypothesis 2 is supported.

Figure 5. Changes in physical activity (calculated as weekly sum of daily physical activity) over time across intervention conditions. One bar equaled either 30 minutes of vigorous activity (eg, gym workouts or swimming) or 60 minutes of moderate activity (eg, jogging). Trajectories show mean physical activity values at 6 measurement points for the VR-gamification, MySugr app, traditional counseling, and control group in the present randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024-February 2025. VR: virtual reality.

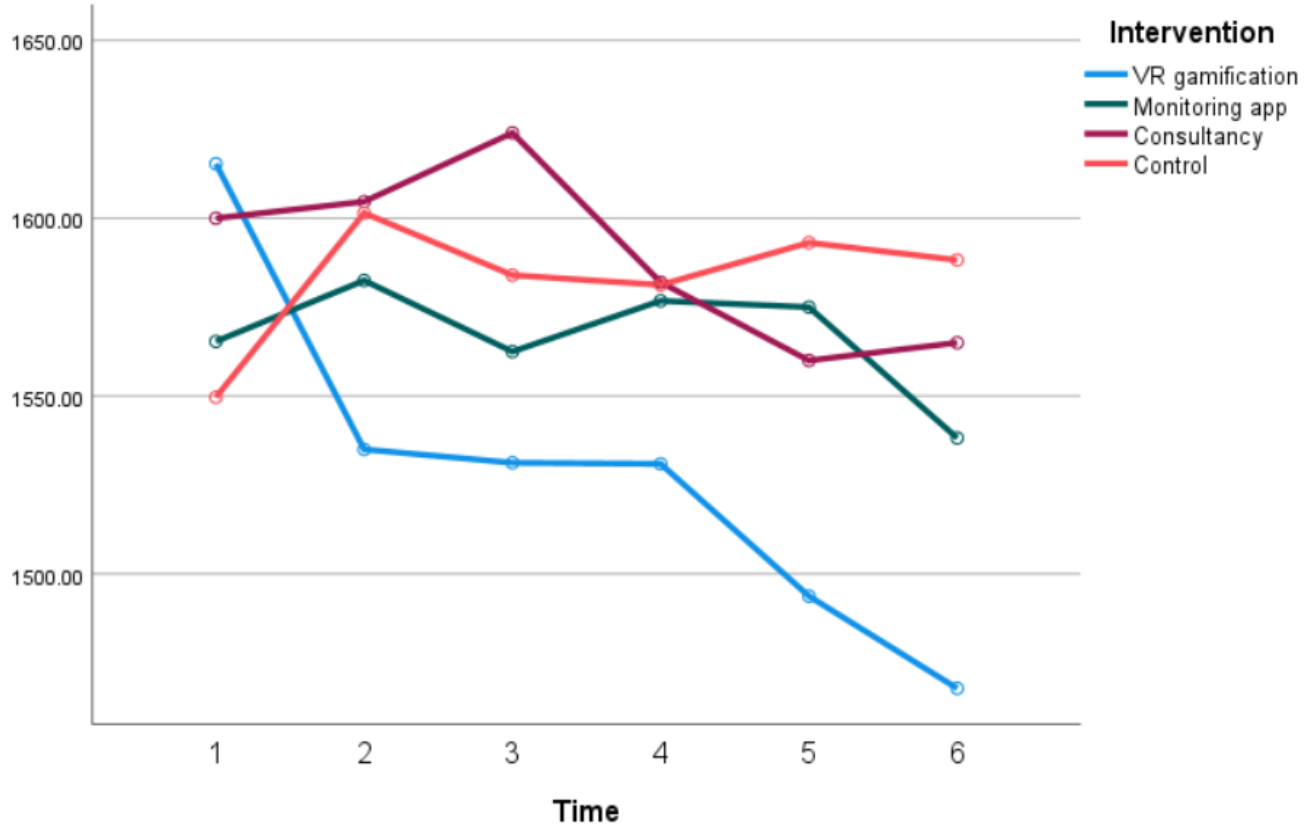


The one-way ANOVA analysis for physical activity during the last session revealed a significant difference in average physical activity between the VR gamified group and the other experimental groups ($F_{3,56}$=21.234; P<.001; partial η^2=.532). A paired-samples t test result showed improvement of physical activity in VR group between the first and last sessions (t_{15}=3.850; P=.002; mean difference=1.625, 95% CI 0.725-2.524; Cohen d=0.963, 95% CI 0.355-1.549). These findings align with recent meta-analytic evidence demonstrating a strong positive effect of exergames on physical activity levels [37].

Food Intake

An LMM was estimated with time**,** condition, and their interaction as fixed effects and a random intercept with an AR1 covariance structure for participants. Model-fit indices (AIC=4138.80) indicated acceptable fit for the repeated-measures design. According to the LMM results presented in Table 2, the main effect of condition was not significant ($F_{3,336}$=0.115; P=.95, partial η^2≈.001), while the main effect of time was significant ($F_{5,336}$=3.487; P=.004; partial η^2≈.059), indicating that the observed downward trend over time was unlikely due to chance. The time×condition interaction effect was significant ($F_{15,336}$=2.794; P<.001; partial η^2≈.111), suggesting that the pattern of change in food intake over time differed between the VR gamified group and the other groups. Random-effects estimates showed large between-subject variability (random-intercept variance=24,595.20,.20; SE 4685.39). The AR1 correlation parameter was reported as ρ=1.000; however, SPSS notes this value is redundant, typically indicating boundary estimation or insufficient information for precise AR1 correlation. Residual variance was 4737.43 (SE 400.39). Figure 6 illustrates the temporal changes in the weekly average calculated food intake across the 4 experimental groups. While food intake fluctuated irregularly in the control, traditional, and app-based groups, the VR gamified group showed a consistent downward trend. Thus, hypothesis 3 is supported.

Figure 6. Changes in food intake (calculated as weekly average of daily calories) over time across intervention conditions. Trajectories show mean daily calorie values at 6 measurement points for the virtual reality (VR)–gamification, MySugr app, traditional counseling, and control group in the present randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024-February 2025. VR: virtual reality.

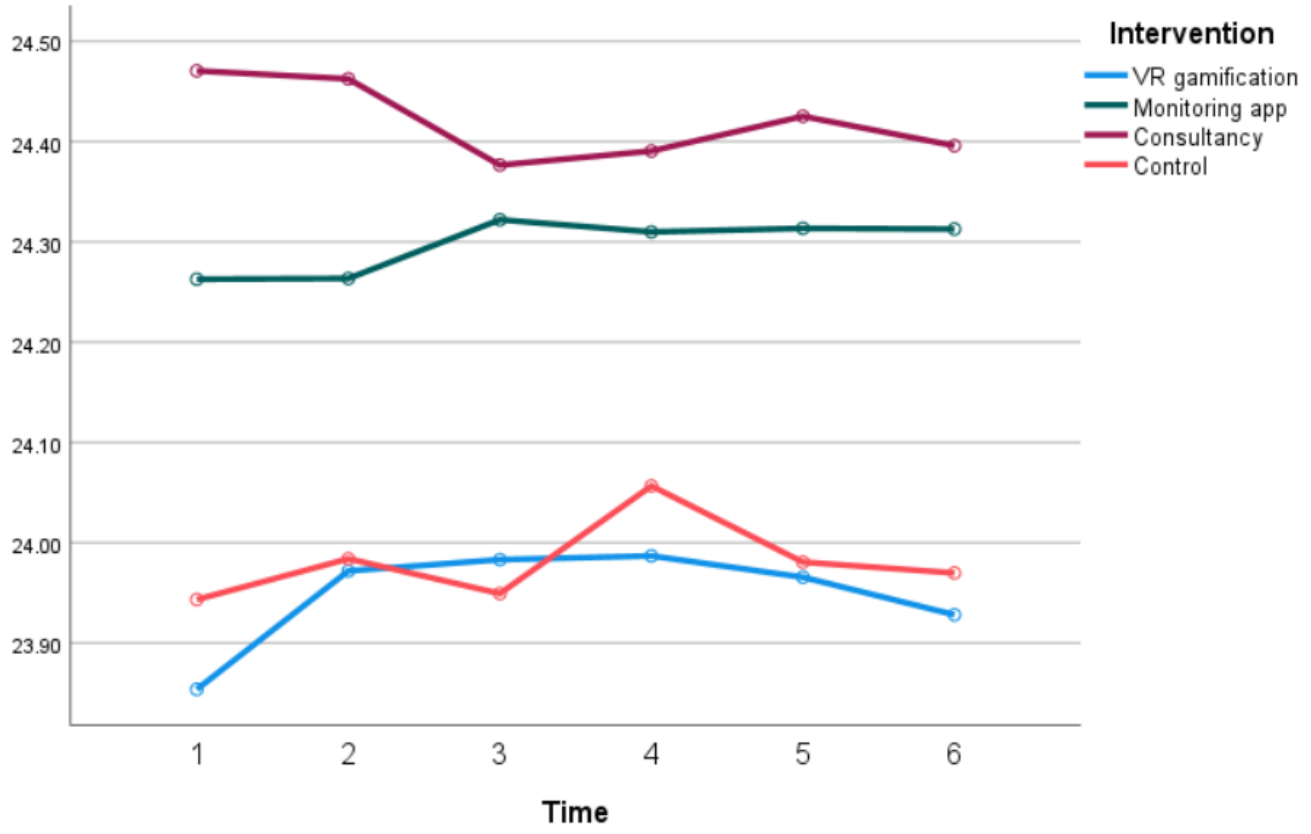


Results of the paired-samples *t* test for the food intake variable in the VR gamified group showed a significant decrease in average food intake from the first to the last session (t_{15}=−3.850; *P*=.002; mean difference=−147.500, 95% CI −0.725 to –2.524; Cohen *d*=0.963, 95% CI 0.355-1.549), which is in line with recent studies [38].

BMI

An LMM was fitted with time, condition**,** and their interaction as fixed effects and a random intercept with an AR1 covariance structure for participants. Model-fit indices (AIC=429.61) indicated that the model adequately captured the repeated-measures structure. According to Table 2, the LMM results for BMI showed no significant effects. For time effect ($F_{5,280}$=0.602; *P*=.69; partial η^2≈.011), for condition effect ($F_{3,40.19}$=0.021; *P*=.99; partial η^2≈.000), and for the time×condition interaction effect ($F_{15,280}$=0.660; *P*=.82; partial η^2=.034). Random-effects estimates indicated substantial between-subject variability (random-intercept variance=21.17; SE 4.32). The AR1 correlation parameter was slightly negative (ρ=–0.209), indicating weak inverse correlation between adjacent repeated BMI measurements. Residual variance was 0.0399 (SE 0.00337). Figure 7 illustrates that the weekly calculated BMI remains relatively stable and consistent across all 4 experimental groups throughout the study period. This suggests that the interventions did not have a significant impact on BMI changes over time. Therefore, hypothesis 4 is rejected.

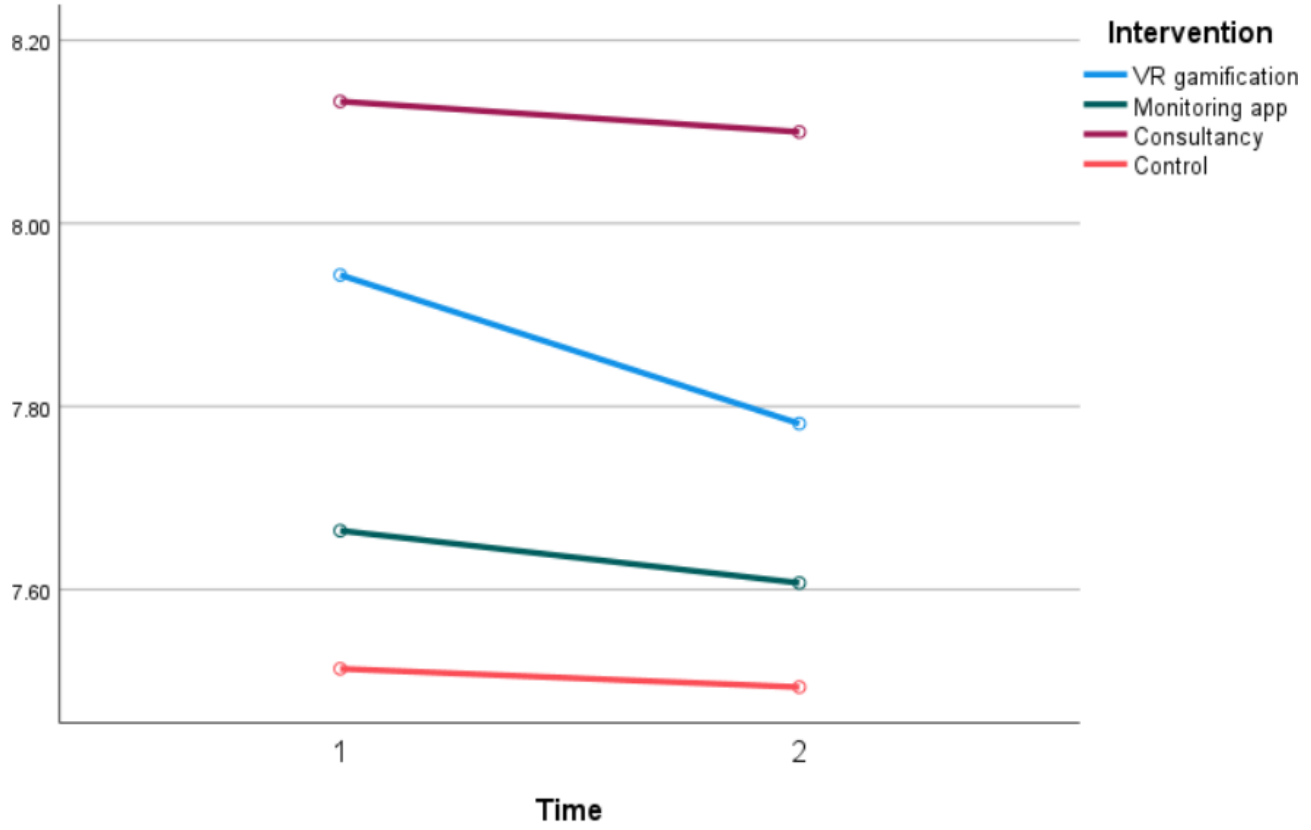
Figure 7. Changes in BMI over time across intervention conditions. Trajectories show BMI mean values at 6 measurement points for the virtual reality (VR)–gamification, MySugr app, traditional counseling, and control group in the present randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024-February 2025. VR: virtual reality.



HbA_{1c}

An LMM was fitted with condition, time, and their interaction as fixed effects. A random intercept for participants was included, and the identity covariance structure was used. The model showed acceptable fit (AIC=306.57). The LMM results presented in Table 2 reveal significant effect for the condition effect ($F_{3,112}$=2.980; P=.03; partial η^2≈.074), the time effect ($F_{1,112}$=0.230; P=.63; partial η^2≈.002), and the time×condition interaction effect ($F_{3,112}$= 0.064; P=.97; partial η^2=0.002). Although the main effect of condition reached statistical significance in the mixed model, this effect reflects baseline differences between groups rather than any intervention-related change**,** as the related effect size is small (partial η^2≈.074). Therefore, no meaningful or clinically relevant effect of the intervention on HbA_{1c} can be inferred. As Figure 8 shows, the pattern of change between the 2 time points did not differ across conditions. Therefore, hypothesis 5 is rejected. Random intercept variance was very small (0.00098), reflecting minimal between-subject variability after accounting for fixed effects. Residual variance was 0.719 (SE 0.096).

Figure 8. Changes in glycated hemoglobin (HbA_{1c}) over time across intervention conditions. Trajectories show mean HbA_{1c} values at 2 measurement points: pretest and posttest for the virtual reality (VR)–gamification, MySugr app, traditional counseling, and control group in the present randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024-February 2025. VR: virtual reality.



Despite the strong correlation between HbA_{1c} and FBS (r_{58}=0.641; *P*<.001; 95% CI 0.469-0.770), our results showed no significant change in HbA_{1c} levels between the pretest and posttest. This finding contrasts with previous studies (eg, Kerfoot et al [39]), which reported significant changes in HbA_{1c} levels over a 12-month period (*P*=.048). The discrepancy may be attributed to the relatively short duration of the current intervention.

Ancillary Analysis

One exploratory analysis was performed, consisting of a correlation analysis to examine associations between behavioral and metabolic outcomes. As Table 3 shows, significant associations were observed between changes in FBS and physical activity (r_{58}=–0.422, 95% CI –0.610 to –0.188; *P*<.001) and between changes in physical activity and food intake (r_{58}= –0.292, 95% CI –0.509– to 0.041; *P*=.02), indicating linked behavioral and metabolic shifts. This pattern aligns with prior findings on the relationship between physical activity and blood glucose levels [40].

Table . Pearson correlations among change scores for trial outcomes. Correlation coefficients show the associations between changes in fasting blood sugar (FBS), physical activity, and food intake across 60 participants of the present parallel group randomized controlled trial study. Population: children and adolescents diagnosed with diabetes (age: 7 - 15 years), Tehran, Iran. Conducted in December 2024-February 2025.

Variable	Changes in FBS[a]	Changes in physical activity	Changes in food intake
Changes in FBS	1	–0.422	0.082
Changes in physical activity	–0.422	1	–0.292
Changes in food intake	0.082	–0.292	1

[a]FBS: fasting blood sugar.

Harms

All XR sessions were completed without any adverse events or early terminations. No instances of cybersickness, visual discomfort, dizziness, or excessive fatigue were reported, and no participant required a session to be stopped prematurely. Adherence to the intervention was exceptionally high, with all children attending and completing all scheduled sessions. Participants in the VR group (n=16) demonstrated high perceived usability, with a mean System Usability Scale score of 74.2 (SD 7.9). According to established usability benchmarks, this value falls within the Excellent range, indicating that the VR environment was experienced as intuitive, consistent, and

easy to navigate. No individual item showed unusually low ratings, suggesting that participants were able to interact with the system with minimal cognitive effort or technical difficulty. TAM responses further supported strong user acceptance of the VR system. Perceived usefulness yielded a mean score of 5.3/7 (SD 0.7)**,** while perceived ease of use was rated 5.6/7 (SD 0.6). These values align with a moderately good acceptance profile, reflecting participants' perceptions that the VR platform was beneficial, motivational, and easy to learn.

Discussion

Principal Findings

The present study aimed to evaluate the effectiveness of a VR gamified program in improving metabolic indicators and health-related behaviors among children and adolescents diagnosed with diabetes. The intervention was compared with 3 comparators, a gamified mobile app (MySugr), traditional consultation, and standard medical care as a control group, in a longitudinal 6-week parallel-groups RCT design. Overall, the results indicate that the VR gamified intervention produced the most consistent improvements in behavioral outcomes, including physical activity and dietary control, compared to the other 3 parallel groups. Moderate yet promising improvements in FBS were also observed in the VR gamified group relative to the other intervention groups, suggesting that the VR gamified method can potentially yield an improved level of short-term glycemic control compared to other methods. In contrast, the intervention did not produce significant improvements in long-term metabolic indicators, including BMI or HbA_{1c}, in the VR gamified group compared to other interventions.

The behavioral outcomes including physical activity and dietary control are consistent with recent studies, indicating that interactive gamified environments can enhance the development of sustained health behaviors [41]. The significant improvement in short-term glycemic control (FBS) alongside a lack of significant improvements in long-term metabolic control markers, including HbA_{1c} and BMI, are in line with recent studies, as long-term metabolic indicators typically require sustained behavioral modification over longer periods to demonstrate measurable changes [42]. The overall improvement trends observed in the VR-gamified group highlight the importance of emotional engagement in self-care interventions. This finding is consistent with previous studies emphasizing that interactive gameplay and immersive audio-visual experiences are critical factors in the success of health gamification systems [43]. In contrast to conventional health-tracking programs that rely primarily on point/badge reward structures, the VR gamified intervention used in this study integrated immersive 3D environments with action-based gameplay that directly represented users' health symptoms and behaviors. Mentioned features may explain the stronger behavioral engagement observed in the VR gamified group and may also clarify why traditional point/badge gamification approaches may produce weaker effects, as reported in some studies [44].

Applications and Limitations

Real-world implementation of this VR intervention could align with existing pediatric diabetes education pathways in which families and educators work together to support self-care. In practice, parents can help supervise home-based sessions, while school health staff may provide complementary reinforcement during the day. Follow-up by diabetes educators or community nurses could be incorporated into routine clinical visits or remote check-ins, enabling the VR experience to serve as an adjunct to ongoing education rather than an isolated tool [45]. However, equitable access to VR remains a challenge. Variability in the availability of VR devices and limited technological resources in some families or schools may restrict adoption. To mitigate such barriers, future implementations may require shared devices in clinical settings or mobile-based alternatives to ensure broader accessibility. Due to the experimental design of this study, the external validity and generalizability of the findings should be interpreted with caution.

Several limitations should be considered when interpreting the findings of this study. First, the relatively small sample size (n=60) may limit the generalizability of the results. Second, the intervention period was relatively short (6 weeks), which may not have been sufficient to observe meaningful changes in long-term metabolic indicators, including BMI and HbA_{1c}. Third, outcomes were measured through self-reported data, which may have caused reporting bias. Future research should therefore incorporate larger samples, longer intervention durations, and objective behavioral tracking tools to provide more robust evidence regarding the effectiveness of VR gamified self-care interventions.

The VR gamified experience developed in this study appears to offer a promising complement or alternative to existing self-care methods, with preliminary indications of potentially enhanced engagement and outcomes. However, interpretations of the behavioral findings should be calibrated to the limitations of measurements, including reporting bias, limited sample size, short duration of the intervention, variations in adherence and fidelity, and the novelty effect of the VR game. Results should be understood as preliminary behavioral signals rather than evidence of clinical improvements. While the program effectively fostered behavioral engagement and adherence trends, no clinically causal inference can be drawn. Future studies with new game mechanics, more engaging designs, larger samples, longer follow-ups, and objective tracking tools can scale the usability of the present intervention and extend related findings.

Conclusion

This study combined gamification elements with immersive VR features to develop a novel self-care system for children and adolescents diagnosed with diabetes. The intervention was grounded in the behavioral economics framework, specifically the theoretical sequence of reward, motivation, behavior, and habit formation, which is central to modern gamification approaches. By offering engaging gameplay within an immersive VR environment, the game established a direct connection between real-life diabetes and in-game mechanics. The goal was to foster intrinsic motivation through in-game

rewards, thereby encouraging users to sustain desirable self-care behaviors. Findings support the potential effectiveness of VR gamified intervention, highlighting its power to serve as a complementary or alternative digital tool for enhancing diabetes self-management. However, clinical implications should be interpreted cautiously.

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The study protocol was developed as part of the first author's (RS) doctoral dissertation of Health Psychology at Tehran University, which is fully documented and accessible. While the designed VR game is available through OSF framework, the source codes and technical tools used during the interventions are provided as supplementary materials to this article.

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This research received no external funding.

Data Availability

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

Authors' Contributions

RS, JH, and RP performed conceptualization, project administration, and methodology. RS and AH performed investigation. AH and AP performed validation and supervision. HBE and RP performed supervision and data curation. RS managed software. HBE conducted formal analysis. RS wrote the original draft. RS, AH, and JH reviewed and edited the manuscript.

Conflicts of Interest

No potential conflicts of interest relevant to this article were reported. The development team of the virtual reality VR game overlapped substantially with the research team conducting the study. The VR game evaluated in this trial was designed and developed mainly by the first author: RS, who was also involved in the trial implementation and manuscript writing. This relationship is disclosed to ensure transparency regarding the study team's connection to the evaluated intervention.

Multimedia Appendix 1
The game source codes.
[RAR File, 9 KB - xr_v3i1e81402_app1.rar]

Multimedia Appendix 2
Diabetes markers data collection form.
[DOCX File, 17 KB - xr_v3i1e81402_app2.docx]

Checklist 1
CONSORT-eHEALTH checklist (V 1.6.1).
[PDF File, 1112 KB - xr_v3i1e81402_app3.pdf]

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Abbreviations

AIC: Akaike information criterion

AR1: autoregressive correlation of order 1
CONSORT: Consolidated Standards of Reporting Trials
CONSORT-EHEALTH: Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth
DM: diabetes mellitus
FBS: fasting blood sugar
HbA_{1c}: glycated hemoglobin
LMM: linear mixed model
MOHME: Ministry of Health and Medical Education
OSF: Open Science Framework
TAM: Technology Acceptance Model
VR: virtual reality
XR: extended reality

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Augmented Reality–Assisted Training Tool for Mental Health Task-Sharers: Pilot Mixed Methods Usability Study

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Abstract

Background: The growing global mental health (MH) burden, especially in underresourced communities, calls for innovative, scalable, and culturally responsive training approaches to expand care access and improve outcomes. Task-sharing has shown promise in addressing workforce shortages but is limited by training and supervision challenges. Traditional methods, such as role-playing and standardized patients, are resource-intensive and less scalable. Virtual simulations, including augmented reality (AR), present novel opportunities for immersive and interactive training. An AR-assisted training tool can enable culturally sensitive training while fostering empathy, communication skills, and confidence in handling nuanced MH scenarios. However, AR's usability and effectiveness for MH task-sharing training remain underexplored.

Objective: This study aimed to assess the usability of an AR-assisted MH task-sharing training tool that uses virtual patient (VP) simulation and evaluate its potential to enhance training. Additionally, we developed design recommendations for future related XR-assisted clinical training tools.

Methods: We conducted a formative, explorative sequential mixed-methods usability study. A convenience sample of 5 MH trainees or workers (ages 18 - 60 years; female: n=3, male: n=2; identifying as African American, Asian, and Hispanic) participated. Participants were recruited through a university-affiliated MH training program. The usability testing protocol included a semistructured prestudy interview, orientation to the AR headset (Magic Leap 2), a think-aloud user testing session, and a poststudy quantitative questionnaire and qualitative interview. Usability was assessed using a modified Post-Study System Usability Questionnaire (PSSUQ), which measures system usefulness, information quality, and interface quality. Data were analyzed using descriptive statistics and thematic analysis.

Results: The AR simulation was positively received by participants, demonstrating above-average usability. The overall mean PSSUQ score was 3.46 (SD 1.71), with subscale scores for system usefulness (mean 3.46, SD 1.77), information quality (mean 3.76, SD 1.73), and interface quality (mean 2.83, SD 1.59). Thematic analysis highlighted high realism fostered trainees' empathy toward the VP, while increasing immersion and interaction quality. Despite some hardware limitations and user discomfort that broke immersion, participants recognized the tool's potential and usefulness for training in various MH scenarios. Based on these findings, we proposed design recommendations across environmental context, training structure, VP behavioral realism (body language, voice, eye movement, and technical hardware considerations).

Conclusions: This pilot study is among the first to evaluate AR-based VP simulation for training lay MH task-sharers, filling the technology and population gaps of prior VR- and desktop-focused simulation research. Preliminary empirical usability evidence from a validated instrument (PSSUQ) demonstrates above-average usability, and findings informed design recommendations for future research. These findings suggest AR-based training could provide a less resource-intensive solution for realistic MH training practice in underresourced settings. Further research includes larger sample sizes for inferential analysis, comparison studies with traditional methods, and generalizing to other MH conditions.

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KEYWORDS

augmented reality; augmented reality glasses; usability; task-sharing; participatory design; mental health care training; role-playing practice; soft skills training; simulation-based training; VP simulation; virtual standardized patient

Introduction

Background

Current Global Mental Health Needs

The worldwide shortage of providers to meet mental health (MH) needs calls for innovative solutions to expand access to care and improve patient outcomes. Depression is a leading cause of global disability; evidence shows that investment in screening and treatment yields substantial health and economic returns [1,2].

In underresourced communities, there are greater barriers to MH care, which calls for context-specific and creative solutions. One factor that may prevent people from seeking appropriate care is MH stigma, which has been found to be higher in racial and ethnic minority populations [3]. Minority groups, including Hispanic and Black communities, are disproportionately affected and less likely to receive treatment [4]. Those who do receive treatment often receive lower-quality services [5].

To address these specific barriers to MH care, there is a need for increasing the supply of providers that exercise cultural humility, as such approaches are more effective at addressing the MH needs of culturally heterogeneous populations [6]. Populations impacted by discrimination and racism often express mistrust of nonminority providers [7]. Addressing these MH care gaps includes expanding appropriate training in cultural competence and instilling humble approaches of care in existing providers [8]. Thus, innovative approaches to training additional providers are needed to meet the growing MH needs of underresourced communities.

Current MH Training Landscape

MH task-sharing is a promising approach for increasing culturally sensitive MH services, particularly in underresourced communities [9]. Task-sharing shifts certain MH services from specialists to less-trained providers [10]. Studies show that task-sharing simple treatments, such as problem-solving therapy and medication management, have been implemented effectively [11,12].

Training and supervision are essential for successful task-sharing, as highlighted by the World Health Organization [13]. Systematic and locally specific efforts are needed to enable intervention sites to design and monitor their own training and supervision [14]. Additionally, simpler therapies, such as behavioral activation delivered by more junior MH workers, have been found to be as effective as more complex therapies delivered by specialists in improving outcomes for patients with depression [15]. Task-sharing interventions are also strengthened by incorporating the services of providers with strong community ties, shared lived experiences, credibility, and nonstigmatizing attitudes [10]. By training these community members and providers who are usually already providing informal support, communities can build their capacity to provide trustworthy MH services.

Resolving challenges associated with supervision and training is essential to improving MH treatment. Although clinical supervision and role-playing are useful training techniques, the conflicting priorities of task-sharing trainees often make it difficult to maintain regular training schedules, hindering the effective implementation of these methods [16]. Additionally, less experienced personnel may struggle to identify and treat subtle symptoms, such as reading facial expressions in patients with severe schizophrenia [17]. This underscores the importance of realistic simulation and accessible, flexible training tools. Traditionally, realistic clinical scenarios have been provided by standardized patients (SPs), trained persons who simulate actual patients and their symptoms [18]. However, this approach is resource-intensive, requiring significant time, travel, financial cost, and supervision [19,20].

Virtual standardized patients are computer-generated, interactive agents designed to simulate clinical presentations, allowing for repeated practice of MH skills such as interviewing and counseling [21]. Because virtual standardized patients do not require the same level of real-time oversight from supervisors, they can alleviate the burden on trainers by enabling self-paced, independent learning.

AR, VR, and Virtual Simulation

Virtual reality (VR) is described as a fully immersive virtual environment, while augmented reality (AR) overlays virtual elements onto the real world [22,23]. AR can foster a strong sense of presence and embodiment, making it a powerful tool in educational and training settings [24,25]. According to research, AR-driven identification and transportation can meaningfully affect users' behaviors, physiological reactions, and psychological perception [26-31].

Social cognitive and situated learning theories support VR's potential for observation-based learning in realistic contexts [32]. VR's immersive and interactive nature also enhances experiential learning, making it effective in training by fostering empathy and user-centered thinking [33]. VR enables high-presence interactions with virtual patients (VPs) and creates realistic training environments [34].

Experiential learning through AR and VR in MH improves users' comprehension, memory retention, and the development of practical skills by allowing them to participate in interactive simulations that closely mimic real-life scenarios [35]. These simulations elicit emotional responses similar to those experienced in real-life situations, nurturing empathy and profound emotional understanding, and providing valuable educational opportunities [36]. Additionally, AR and VR allow learners to practice in realistic environments, developing key skills like procedural recall, communication, problem-solving, and coping strategies [37]. Furthermore, AR and VR have been shown to be interactive, engaging, and convenient, hence making them valuable tools for virtual simulations in MH training and task-sharing settings [38].

Landscape of VR Training

VR training is increasingly used in health care education for both technical and nontechnical skill development [39,40]. In nursing education, a review of virtual simulations found them to be as effective as, or more effective than, conventional methods, offering self-paced, economical, and space-efficient learning opportunities [41].

In MH nursing, VR simulations facilitate emotional connections between learners and VPs by presenting realistic, interactive scenarios [42]. While earlier studies used nonimmersive, desktop-based VR, immersive VR with head-mounted displays (HMDs) has shown greater efficacy due to its sensory immersion, which intensifies focus, presence, emotional engagement, and learning outcomes [43-48]. In a usability test, a 360-degree VR simulation portraying schizophrenia scenarios was found to be user-friendly, engaging, educationally relevant, and highly immersive [49]. Another study on VR simulation training for behavioral health anticipatory guidance and motivational interviewing found that VR significantly increased pediatric residents' engagement and critical skill development by providing an immersive, accessible, and realistic but patient-free learning and practice environment, and reduced their anxiety and stress [50].

Landscape of AR Training

AR is easier to use and has fewer negative physical side effects than VR, including the "cybersickness" that is sometimes felt after long VR usage [51]. AR also increases knowledge transfer by including real-world context that VR does not have [52]. In the medical field, AR is gaining popularity as a tool for clinical training and patient education by enabling medical professionals to visually communicate information about new treatments, medication mechanisms, and surgical procedures [53-56]. AR's applications in anatomical and physiological training are noted for their maturity, showing substantial promise for transforming medical education through innovative prototypes and teaching approaches [57]. An integrative review by Zhu et al [58] found that AR has the potential to improve health care education by lowering failure rates and enhancing precision, while other studies also highlight AR's role in enhancing knowledge retention, concept integration, and confidence among medical students [58-62]. For example, a pilot study contrasting traditional mannequin-based training with AR-enhanced approaches for patient decompensation recognition demonstrated that AR significantly improved participants' assessment skills and clinical confidence [63]. Despite promising early findings, there are still relatively few published experimental and observational studies assessing AR's application and efficacy in medical education [23].

AR in medical education has shown promise in enhancing learning and practical skills, and it has further potential in providing immersive environments for the development of important social skills [64]. By superimposing virtual components within the real environment, AR is very suitable for effective simulation training [58]. Ward et al [65] expressed that exposing users to challenging or rare scenarios in AR simulations creates a safe environment for practicing adaptive skills needed in the clinical space. Despite AR's potential to deliver intricate and precise training across diverse social skills applications, the literature remains lacking, especially within MH training. A recent systematic review pointed out that while simulation-based training in health care education is advancing, there is limited systematic research on its impact on learning outcomes, with most studies to date focusing on feasibility and face validity [64].

Using an AR tool for MH simulation training with VPs is novel; hence, usability testing, defined as the evaluation of elements that impact users' experience with a product for its intended purpose, is an essential first step to determine the strengths, weaknesses, and effectiveness of using AR for task-sharing [66]. Thus, we conducted a mixed-methods pilot study assessing the usability of our AR tool.

Research Objective

Building on the above existing research, we first engaged in a participatory design process to investigate the various needs and challenges pertaining to AR-assisted training of lay MH workers in conducting MH screening and assessments of community members. We then built a prototype which was pilot-tested with stakeholders from the Harlem Strong Initiative (HSI). The HSI, led by the CUNY Center for Innovation in Mental Health (CIMH) team, uses community-engaged planning across a multisectoral coalition of organizations to support MH task-sharing and evaluates the impact of this model in low-income housing and primary care sites in the Harlem community [67,68].

The goals of this study are to assess the usability of the AR-assisted MH task-sharing tool in the current training landscape and to propose design recommendations for future iterations of AR-assisted training tools for MH task-sharing skills and related use cases.

Methods

Research Design Overview

The study design used a formative mixed-methods approach incorporating both qualitative and quantitative data. This design triangulates objective usability scores with subjective user experiences. We chose a modified "think-aloud" protocol for user testing to gather insights into study participants' cognitive processes and any usability difficulties they had during the experience [69]. As a group, we outlined questions for pre- and posttesting qualitative interviews grounded in literature, and we used the Post-Study System Usability Questionnaire (PSSUQ), which has prior validity evidence to assess usability quantitatively [70].

Prototype

The prototype was co-designed with community leaders and members of the Harlem community. Methods used during the participatory design included interviews, field ethnography and observations, early user testing workshops, and multistakeholder co-design sessions.

To better understand and design for the community, we explored three research questions: first, what are the various needs and challenges pertaining to training community-based organization workers in conducting MH screenings of community members; second, how can an AR-assisted MH task-sharing training tool potentially address those needs and challenges; and third, what interaction design strategies can be used to improve the usability of such a tool.

Interviews and brainstorming workshops with community stakeholders highlighted key needs for the training tool- being

time-efficient, offering engaging and realistic content mirroring the nuanced scenarios social workers often face, catering to diverse backgrounds, especially the African American and Hispanic communities, while accommodating varying levels of MH literacy, embedding emotional support for social workers during intense scenarios, and fostering a sense of self-efficacy.

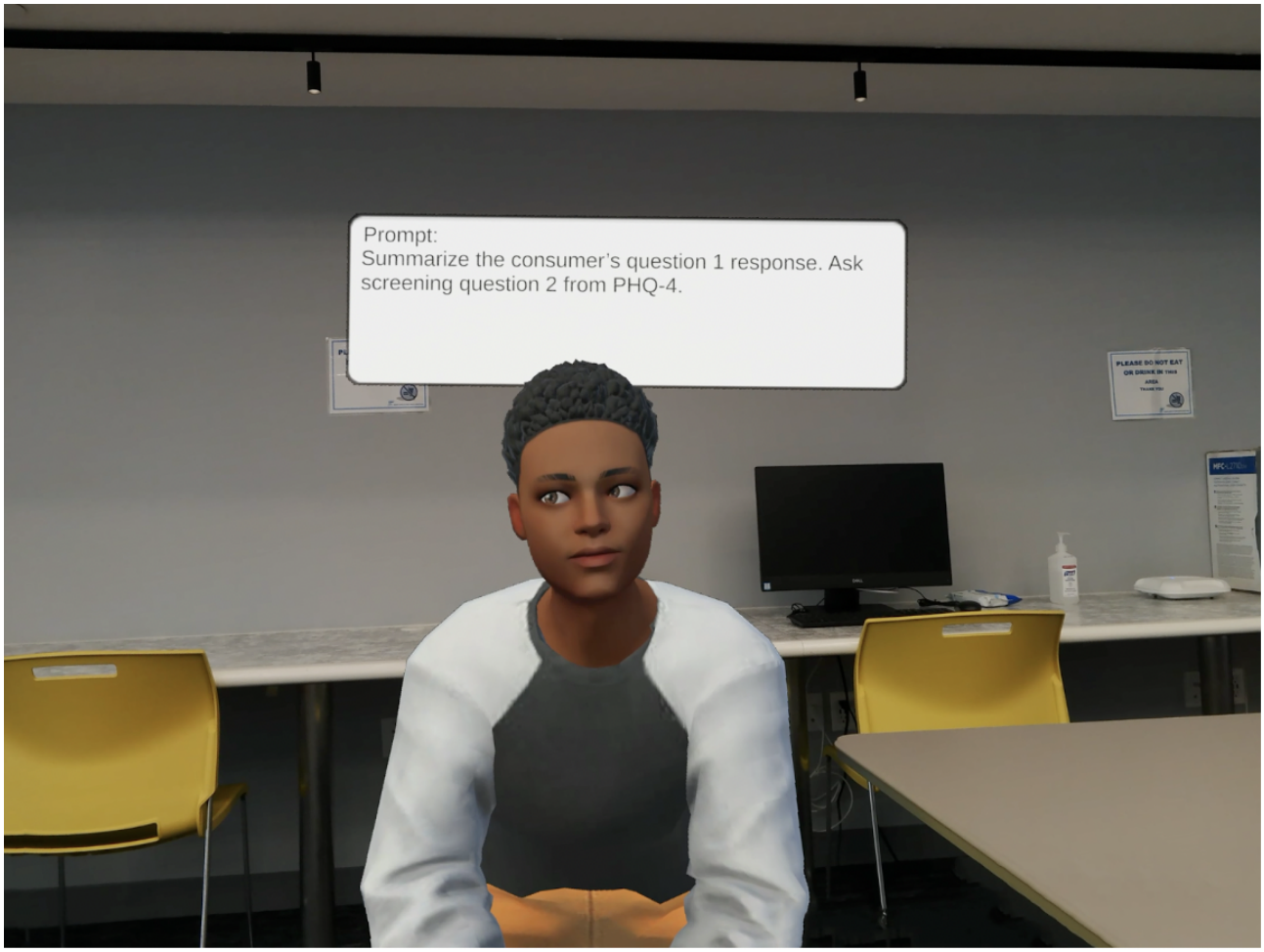
During a field observation session of CIMH's existing online training, screening skills were highlighted as a curriculum section that many trainees wanted to explore further. The Patient Health Questionnaire-4 (PHQ-4) form specifically offers a self-contained, well-structured, brief training scenario that requires soft skill expertise to administer effectively. It consists of four questions that assess symptoms of both anxiety and depression, frequently used for clinical assessments and research purposes [71]. Thus, administering the PHQ-4 was integrated into the design of the prototype.

After several co-design sessions, the prototype was finalized as a single MH screening skills module guiding trainees through administering the PHQ-4 appropriately (Multimedia Appendix 1). As seen in Figure 1, the user puts on the AR glasses, Magic Leap 2, and role-plays as an MH provider and interacts with a young adult, Hispanic, male VP named Alvaro, who exhibits symptoms of depression and hesitates about opening up about them [72].

Trainees are guided by 24 different dialogue prompts (Multimedia Appendix 2) that appear above the VP in a roughly 10-minute simulated interaction (Figure 2).

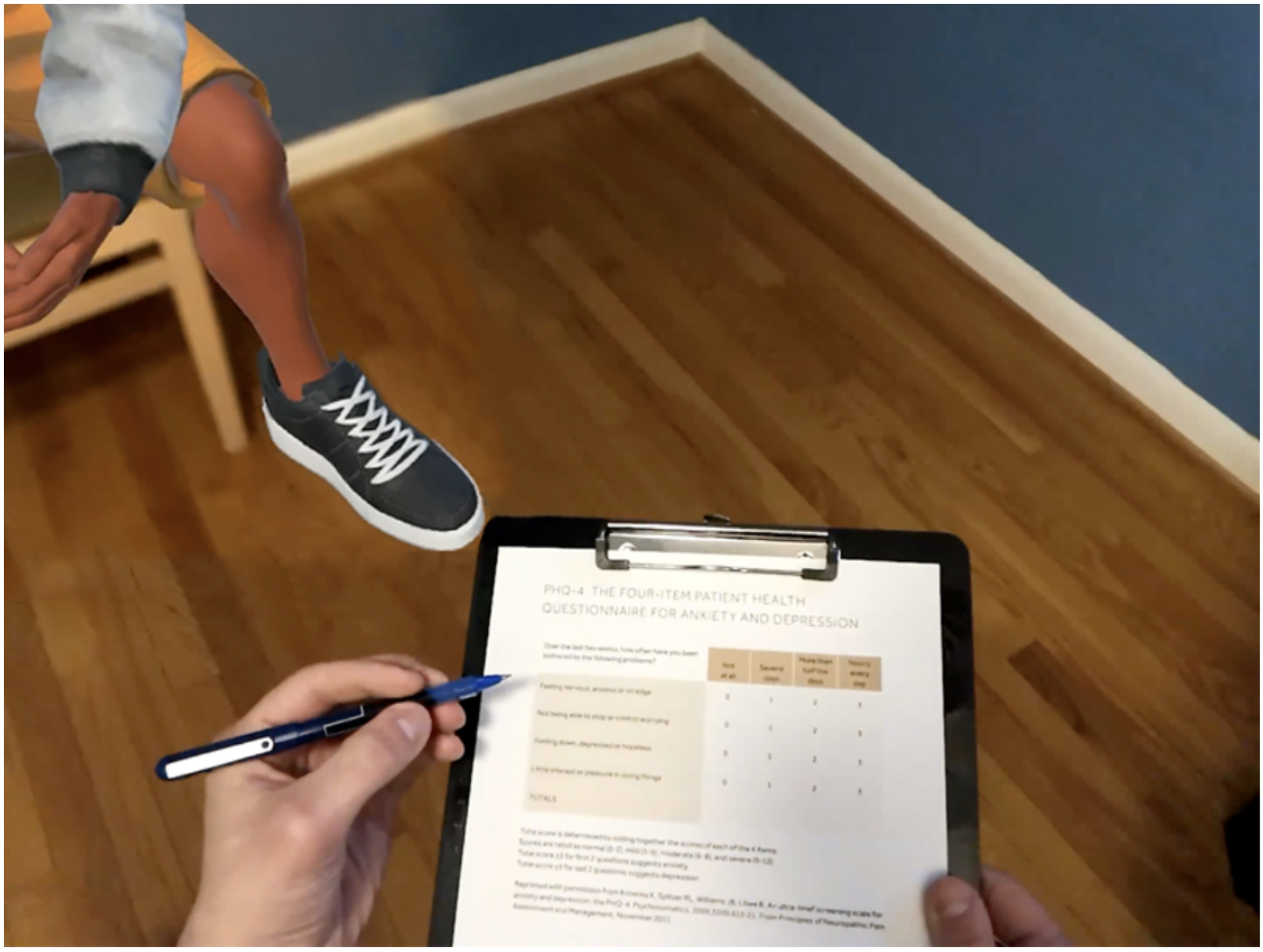
Figure 1. Profile view of a participant wearing the Magic Leap 2 augmented reality headset while interacting with the virtual patient training prototype. The virtual patient appears through the headset and is positioned across from the participant to simulate a face-to-face mental health screening and communication scenario.

Figure 2. First-person headset view of the virtual patient embedded within the real-world lab environment. The virtual patient is designed to simulate conversational screening interactions and respond to user input during the augmented reality-based training experience. PHQ-4: Patient Health Questionnaire-4.



The VP responds with human-recorded spatial audio voiceovers, lip-synced to animated facial expressions, as well as various body language animations, which enhance the realism and emotional aspect of the experience. Trainees can ask follow-up questions at times or ask the VP to repeat what they said. The experience allows them to practice new communication skills verbally and in an embodied way, engaging with the VP while filling out four responses on a physical PHQ-4 form (Figure 3).

Figure 3. First-person view of the Patient Health Questionnaire-4 screening form presented during the simulation. Participants completed the standardized questionnaire as part of the virtual patient interaction workflow. PHQ-4: Patient Health Questionnaire-4.



Data Collection

Participants

A convenience sample of participants was recruited from CIMH's community network through listservs and word of mouth. Inclusion criteria were broad to capture a wide range of task-sharing perspectives, requiring that participants were members of or adjacent to the community served by the HSI and could speak to the needs of local MH training. Participants recruited for this study group did not overlap with study participants in the main HSI study. Education and MH training levels were varied to generalize the usability of the training tool; participants ranged from a college student with no MH training to an experienced licensed clinical social worker. While five participants were initially recruited and consented, one participant withdrew before beginning the user testing stage. Consequently, the final analytical sample consisted of four participants (n=4), representing a 20% proportion of missing data for the simulation and poststudy measures.

Usability Tests

There were 5 back-to-back usability tests scheduled in a day, with each session lasting between 45 minutes and 60 minutes. Participants were compensated with a US $50 Amazon gift code for their contributions. Their informed consent was first obtained through a physical form, after which we carried out a five-stage data collection procedure:

Participants first engaged in a semistructured prestudy interview, detailing their training background, including their experience with CUNY's MH skills modules and their role in the community. They also discussed the challenges and strategies associated with interactions with distressed community members who could be experiencing MH issues. (Multimedia Appendix 3).

Participants were then briefed about the study goals and AR simulation objectives. They were provided with clear instructions about the AR glasses usability test, emphasizing the experience over their knowledge.

After an orientation to the AR glasses, participants navigated an AR simulation, practicing the administration of the PHQ-4 form with a VP. To facilitate the "think-aloud" protocol, researchers provided a structured briefing and used standardized verbal probes during the simulation. Participants were prompted to describe visual elements (eg, "Describe what you see"), instructed on how to handle interaction cards (eg, "Show us how you would proceed"), and asked targeted questions during planned pauses regarding the character's body language and the use of the PHQ-4 task. If participants deviated from expected interactions, researchers asked clarifying questions such as

"What did you expect to happen?" to capture their cognitive processes.

A semistructured poststudy interview guide was used to assess participants' perceptions of the usability of the AR simulation (Multimedia Appendix 3). Interview guide questions were adapted from usability testing literature [73-75]. The interview aimed to query feedback on the prototype's use, effectiveness, and potential improvement areas. At the end of each interview, the researcher confirmed all relevant information had been included to ensure the quality and accuracy of the data.

Finally, a 17-question poststudy questionnaire (Multimedia Appendix 4), adapted from the PSSUQ with a 7-point Likert scale ranging from strongly agree (1) to strongly disagree (7) with N/A as an additional option [70], was administered. The PSSUQ is a validated instrument with high internal consistency (typically Cronbach α>0.89), designed to measure user satisfaction across system usefulness, information quality, and interface quality. Additionally, demographic questions with multiple choice options were included that determined Table 1.

Table . Overview of interview participant characteristics, including age range, gender, ethnicity, prior augmented reality experience, and highest level of education. One enrolled participant withdrew prior to completing the study.

Participant ID	Age range (years)	Sex	Ethnicity	No. of times used an AR[a] or similar device	Highest level of education
P1	35 - 40	Male	Latino or Hispanic	0	Master's degree
P2	26 - 30	Female	Asian	1	Bachelor's degree
P3	56 - 60	Female	African American	0	Master's degree
P4	16 - 20	Female	Asian	0	High school
P5 (dropped out)[b]	—[c]	Male	African American	—	—

[a]AR: augmented reality.

[b]Participant wore glasses, went to get their contact lenses but never came back.

[c]Not available.

The testing took place at one of CIMH's facilities, in a large private room with several tables and chairs. The first and second authors conducted the usability tests and were the only people present in the space besides the study participant. The hardware used includes the Magic Leap 2 and two laptops for filling out the study questionnaires. The prototype was developed in Unity, using Ready Player Me for the custom avatar, Salsa LipSync Suite for facial animations, and Mixamo for body animations [76-79]. The usability lab featured two facing chairs (Figure 4), one for the participant and one for the VP. Researchers were positioned outside the participant's field of view (Figure 5) and intervened only for technical issues or at specific checkpoints (Multimedia Appendix 3).

Figure 4. Individual participant setup during usability testing, showing the seated configuration used for augmented reality-based virtual patient interaction and observation.

Figure 5. Usability lab setup including facilitator workstations and participant seating arrangement used during augmented reality training sessions.

Data Analysis

Quantitative

We used descriptive and summary statistics to analyze participant demographics and scores on the adapted PSSUQ. Due to the pilot nature of the study and the small sample size (n=4), inferential statistical testing was not performed; data are presented as mean (SDs) to indicate trends.

The PSSUQ consists of a set of 17 questions on a 7-point Likert-scale (1=strongly agree to 7=strongly disagree). The overall PSSUQ score is the average of the scores of questions 1 to 15 and 17. The subscales include: system usefulness (SYSUSE), which is the average score of questions 1 to 6, information quality (INFOQUAL), which is the average score of questions 7 to 12, and interface quality (INTERQUAL), which is the average score of questions 13 to 15.

Qualitative

All interviews were recorded using Zoom, with identifying details removed to maintain confidentiality [80]. Initial transcriptions, facilitated by Zoom's automatic service, were refined by the first author, taking out any names, occupations, and other identifying details and using a prescribed participant number instead. After transcriptions were verified for accuracy, they were entered into the qualitative analysis software ATLAS.ti (ATLAS.ti Scientific Software Development GmbH), where a 2-step coding process was adopted [81].

Two independent coders (VN and SF) were used to minimize bias and positionality and ensure accurate depiction of participants' perceptions [82]. The first author (VN) and a research assistant (SF) used an inductive approach based on conventional qualitative content analysis to analyze the interview data [83,84]. In contrast to summative content analysis, which focuses mostly on counting and measuring data, this method emphasizes the identification of recurrent patterns throughout the data collection, similar to traditional thematic analysis [85].

The researchers independently reviewed the interviews and subsequently coded key concepts in line with the interview questions while also drawing from codes from the participatory design phase, such as "Challenges," "Workflow," "Ease of use," "Immersion," "Usefulness," and "Future recommendations." Then, the researchers discussed preliminary findings since multiple analysts for code development enhance the findings' credibility [82]. Using an open coding strategy, codes were refined and added, reflecting significant patterns in the data. Discrepancies in coding led to discussions until consensus was reached. The frameworks described in a related study by Hess et al [86] served as further guidance for the coding process. Domains from the study like "Experiential satisfaction," "Learning engagement," "Technology learning curve," and

"Opportunities for improvement" formed the basis for theme identification.

Transcripts were then restructured according to common codes for thorough examination of themes and patterns. Participants' frequently overlapping and closely related codes were grouped together to create categories, which in turn led to the formation of primary themes. The categories were formed and summarized individually. Comparing these categories and summaries between the 2 researchers constantly and discussing to reach consensus allowed for principal themes (Multimedia Appendix 5) to be formed with a consistency of more than 90%, suggesting additional reviews were unnecessary [82].

Ethical Considerations

This study was approved by CUNY's Institutional Review Board (IRB2021-2031) as part of the Harlem Strong Mental Health Coalition study (U01OD033245). All procedures performed were in accordance with the ethical standards of the institutional and/or national research committee, and written informed consent was obtained from all participants. The consent forms included information on the study purpose, expected procedures, time commitment, potential risks, discomforts, and/or benefits, such as participation payment, and participant confidentiality and rights. Participants were given descriptions of how and with whom their data would be safeguarded, used, and shared; details in the consent form included the potential for deidentified data submission to the National Institute of Mental Health Data Archive (NDA) for secondary analysis without additional consent.

Authorized members of the research team managed the password-protected data for any identifiable information that might be linked to participants from this study. Codes were assigned to replace names of participants, and identifying information was removed when no longer needed. Participants were compensated with $50 Amazon gift cards after the completion of their session. In terms of included images of participants completing the study, only the study team members are identifiable in photos. Participants all wore the AR headset, and written permission was obtained to include their deidentified images.

Validity, Reliability, and Methodological Integrity

In accordance with JARS-Qual standards, we acknowledge the influence of the research team's background on data interpretation. The primary investigators include digital health informaticists, HCI researchers, and clinical psychologists with extensive experience in MH task-sharing. This diverse expertise allowed for a rigorous evaluation of the tool's technical performance while remaining grounded in clinical reality.

Quantitative reliability was supported using the validated PSSUQ instrument. Qualitative integrity was maintained through investigator triangulation and the use of the think-aloud protocol, which captured real-time cognitive data, reducing retrospective recall bias.

Results

Overview

We recruited a total of 5 lay MH trainees and workers with various ranges of training and experience in MH care (for participant details, see Table 1).

Prestudy Interview

To set some context for this inquiry, we present a brief background of relevant current workflows described by the pilot study's participants during the prestudy interviews.

Building Trust Is Challenging but Important

Building trust with the community was highlighted as crucial by two participants. P1 told us that they

> *definitely use a lot of open-ended questions,*

While P3 highlighted that

> *Trust is a huge factor in getting community members to know that you're there for them, that you're concerned about their well-being. You'd like to maybe introduce them to some practices that they may not be aware of or might not understand fully and let them know that it's okay.*

P3 further described:

> *I might tend to go a little bit further than intended for whatever the session is supposed to be, as more of a listening ear type thing, and just try to engage in trying to get more information from them that I might not necessarily use.*

Difficulty in Adapting Theoretical Knowledge to Practice in Current Training

Participants experienced difficulty adapting theoretical knowledge to practice. P2 noted that

> *because every encounter is different, it's kind of very foundational. You have to develop your own way of counseling,*

While P1 emphasized that

> *when you come into actually working in the field, it's a little different. You might be in a setting where you're dealing with things that are the least favorable settings.*

Current Training Included Role-Play and Usually Did Not Include Difficult Scenarios

P1 told us that in the current workflow they: "*covered* The *Diagnostic and Statistical Manual of Mental Disorders*," which is a comprehensive classification system published by the American Psychiatric Association (APA), and "*did a lot of role-play.*" They added that "*normally, when we do role-plays in class, nobody goes down that road of re-enacting more challenging scenarios like schizophrenia, people tend to present the lighter stuff that might not be entirely accurate.*" This highlighted that current training included role-play and usually did not include difficult scenarios, which corroborated with our prototype design to focus on role-play.

Content of Sessions

P1 also noted that typical sessions were brief:

> *Most of the sessions that I work with were 20 min sessions. So if I only had 20 min to gauge how a person's week went, you know, to go through anything larger than 5 questions to gauge their temperament will be challenging.*

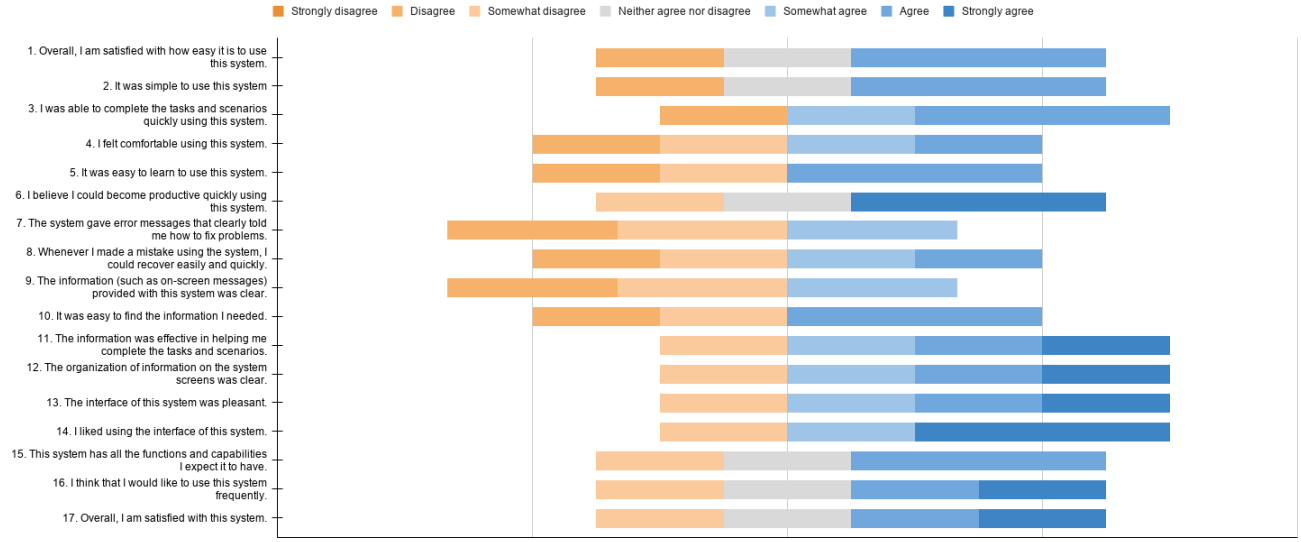
This informed our prototype design choice of administering the brief PHQ-4 form.

Usability Findings

Overall, the four participants rated the usability of the prototype as above-average usability (Multimedia Appendix 6) in the modified PSSUQ survey which includes an additional question on the desired frequency to use the system (question 16).

The prototype received an overall PSSUQ score of mean 3.46 (SD 1.71), SYSUSE score of mean 3.46 (SD 1.77), INFOQUAL score of mean 3.76 (SD 1.73), and INTERQUAL score of mean 2.83 (SD 1.59). Desire to use the system frequently (question 16) received a mean score of 3 (SD 1.83). Figure 6 displays the distribution of responses across all items. One participant chose N/A for questions 7 and 9, which skewed those results. Participants who identified as Asian experienced difficulty with the headset fitting comfortably on their faces (due to a missing nose piece kit) and gave higher scores on their PSSUQ questionnaire.

Figure 6. Distribution of participant responses to the Post-Study System Usability Questionnaire. Bars leaning toward agreement indicate positive perceptions of system usability. N/A responses were excluded from the visualization.



Think-Aloud Insights

In this section, we outline the observations made during the think-aloud section in which participants interacted with the intervention.

Use of Physical Headset

Two out of the four participants experienced the headset falling off their face, requiring constant adjustment and even manual holding to continue. P2 mentioned that

> *it broke the immersion to me. I think it would feel more like I'm talking to someone if the headset didn't keep falling, I was distracted by it.*

P4 felt similarly:

> *it's just slipping down everywhere. My arms were like sore from holding it up because they're heavy, too. But yeah, I think I was a little bit distracted by how like it kept falling down. I think also like the whole thing with the headset not fitting just like took away from it.*

By P4's session, the headset was also heating up, compounding discomfort.

Delivery of Content

All participants reported difficulty hearing the VP's audio at maximum volume, requiring researcher clarification at multiple points.

P3 and P4 also reported difficulty understanding the VP's accented speech at times, with P4 unable to comprehend certain responses even after replays.

P2 and P4 experienced technical glitches where the VP failed to respond to prompts, requiring researcher intervention to continue.

Key Themes From Postintervention Interviews

Following the think-aloud section, the study's major themes identified from the postintervention interviews are discussed here, mainly experiential satisfaction, navigation of the training experience, and interacting with the VP.

Experiential Satisfaction

The overall impression of the simulation, particularly the emotional valence and level of satisfaction for the participants, was generally positive, consistent with the above-average overall PSSUQ usability score (mean 3.46, SD 1.71). The simulation's realism allowed for participants to feel empathy toward the VP. Participants acknowledged the potential usefulness of the

simulation in other contexts, and first-time AR and VR headset users also voiced some struggles.

General Positive Sentiments

Participants generally had positive sentiments toward the training module and found the simulation to be very useful. P2 expressed that "it's a really good training module and the prompts were very helpful in guiding." Echoing similar sentiments, P3 pointed out that this was their first AR and VR experience and that "it was cool and successful." Drawing connections to current training, P1 mentioned that adding this kind of training and technology would be beneficial for practicing difficult cases during role-playing training as they could better depict challenging scenarios. They emphasized:

> *I think maybe having specific augmented reality trainings for specific DSM categories would be very helpful … like depression and anxiety … if it's tailored towards, you know, something that may be heavier, that would be interesting.*

Furthermore, they highlighted that the usage of the PHQ-4 form itself would be useful for training as it would also be helpful to use it in the field.

Realism Resulted in Empathy for the VP

The realism of the simulation and the quality of the animations led participants to feel empathy toward and connect with the VP. Participants all expressed that they felt like they were talking to a real person, and some also mentioned that they forgot that the researchers were in the same room while having the conversation, as the simulation felt so realistic. Three out of the four participants also noted that the voice of the VP felt very realistic as it had an accent, making the scenario very similar to what it would be like in the field. P1 emphasized that

> *it kind of forces you to empathize. It forced me to look at the AI almost like a real person, like, this person has an accent.*

Potential Usefulness of Simulation in Other Contexts

Furthermore, participants highlighted the potential usefulness and applicability of the training approach in other contexts, especially in different MH and specific *DSM* (*Diagnostic and Statistical Manual of Mental Disorders*) categories. Other contexts mentioned include general one-on-one interactions, for example, in customer sales training. With regards to other MH contexts, P1 pointed out that it would be a lot more beneficial to carry out challenging role-play scenarios through AR than to act them out, as it may misrepresent symptoms of, for example, schizophrenia. P3 also highlighted that it would be extremely useful to have simulations like this used in the context of different MH conditions, as having and practicing the lived application of this knowledge is important for people who interact with people who might display these conditions.

Struggles for First-Time AR and VR Headset Users

Two out of the three first-time AR and VR headset users told us that they were slightly confused at the start when trying to navigate the experience. They felt a little overwhelmed between having to pay attention to the prompts, ask questions from the PHQ-4 form, and pay attention to the VP's speech while trying to understand the accent, be attentive to the VP's body language, and maintain eye contact. The uncertainty of what would come next initially also made the participants feel uneasy. On the other hand, P1 told us that

> *if this was my second or third practice, I would know I can read the prompt and look at the patient.*

Two participants mentioned that with more practice, they would be able to get the hang of the training and reap the benefits from it.

Navigating the Training

This section details the participants' experience with the system's guidance mechanisms, providing context for the information quality subscale (mean 3.76, SD 1.73), where the instructional design was found to be functional but occasionally confusing.

Effectiveness of Prompts

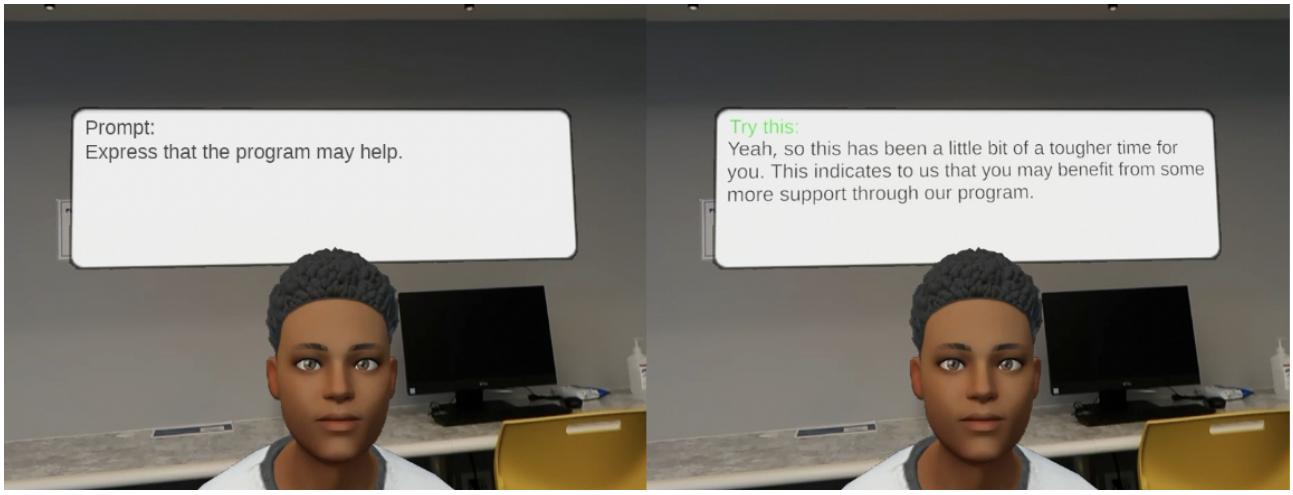
Overall, participants found the prompts (Figure 7) useful in guiding them through the training. P3 appreciated that the prompts helped them focus on the specific goal at that certain time and that the prompts worked well in helping them follow the flow of the training. P4 mentioned how the prompts helped them to learn appropriate responses when they were unsure of how to respond. They told us:

> *I'm not sure if Im like you know, helping or hurting. So that's why having the prompts helped. It's like semantics also have impact on how you affect the client ...*

They further mentioned that

> *… at times I was really lost as to what to say, but also because I didn't hear him so well. That kind of made it more helpful for the prompt, because I was like, okay, this is what I say now.*

Figure 7. Comparison of two in-system prompt styles within the virtual patient simulation: (left) a general guidance prompt encouraging users to respond in their own words, and (right) a structured "Try this" prompt offering a suggested phrasing. The figure illustrates alternative scaffolding strategies tested for communication support.



However, navigating between 2 types of prompts (Figure 7) confused users and reduced immersion. Participants mentioned that having to pay more careful attention to the 2 different kinds of prompts broke the flow of immersion and took away from the experience. P2 elaborated that

> *when it's the 'Try this' prompt, I'm like kind of fed what to say, but then there's the other prompt where I kind of have to think on my feet. Switching back and forth was kind of confusing for me.*

P3 and P1 similarly felt that the simultaneous demands of attending to VP dialogue, body language, and PHQ-4 questions alongside varying prompt types created cognitive overload. P1 wanted more attention to the VP's "body languages, whatever it may be, tone of voice, things of that nature," hence the navigating between the 2 prompts did sometimes confuse them.

Administering the PHQ-4 Form

Participants pointed out that it was difficult to interpret qualitative responses and translate them into a quantitative scale (PHQ-4 form). P1 told us that

> *At times, I was unable to gauge like an appropriate answer from his response so I wanted to interact with him more to see what that meant. I felt like I needed to pull more.*

They further elaborated that they wanted to ask the VP more clarifying questions and have a more dynamic interaction to get the correct scale reading. P4 brought up that people usually don't know how they feel, and it is MH workers' jobs to be their advocate and interpret their response into a number and understand how to help them. Yet P4 expressed that

> *it really depends on the mental health professional right? Who is speaking to them like, what do they think that his, or her, or their response means, and translate all to a quantitative scale, which is difficult.*

Interacting With the VP

In this section, participants' interaction with the VP will be reported, mainly their listening to the VP, observing the VP, and the flow of conversation with the VP. These qualitative insights help explain the strong interface quality score (mean 2.83, SD 1.59) attributed to the VP's realistic body language, as well as the auditory challenges that impacted the Information Quality subscale (mean 3.76, SD 1.73).

Listening to the VP

Participants found that using a real person's voice with an accent increased realism, immersion, and hence the usefulness of training for specific populations or communities. P1 remarked that the VP's accent is very realistic, which reflects people in the community having different accents that might be more difficult to understand. P4 echoed this and felt like the voice was real because it had an accent. P4 elaborated that

> *If it was an automated voice I would have felt weird, that would have added to like the whole unrealness. Using a real person's voice definitely helps… yeah, at one point… like it hit me that he wasn't actually there. It was like just the two of us having a conversation.*

Although P2 felt that the voice was impactful, they mentioned, "I wasn't sure how to respond, because I couldn't understand. I think his accent, and also like the volume was low."

All participants experienced difficulty with hearing due to low volume and accent. However, this motivated them to listen more intently during the training, and they expressed that it was beneficial to train for real-life situations in which some people are more soft-spoken. P1 raised that "it trains me to hear, so it does serve a benefit" echoing P2, who noted "in a real-life situation, when someone is speaking softly or in a different accent, I would need to be listening more intently." P4 reiterated "I really had to process, really listen, which is good, I was really listening."

Observing the VP

Overall, participants highlighted that the body language of the VP was useful in training and increased realism, immersion, connection, and empathy. P1 mentioned that nonverbal cues were extremely helpful, for example, "the moving forward, the eyebrow expression." P3 echoed the movement of the VP:

> *He actually felt kind of connected … there was a point where he kind of leaned back. I felt like it was important to just kind of lean in just a little bit to let him know that I heard and to let him know that he was okay. And I think that that's so valuable and so important. It's kind of given that empathetic piece.*

Similarly, P4 also expressed that they felt empathy and connection toward the VP, highlighting that

> *when he leaned forward, I think maybe it was sort of his way of saying like, 'Oh, this is between me and you, like when he was sharing whether he was feeling depressed.*

P4 further inferred from the movement that "He was afraid that I would tell others. So I think that's why he leaned forward."

On the other hand, there were mixed views on the realism of the VP. P4 mentioned that the distance of the VP in the headset facilitated easier conversation with the VP. They highlighted,

> *I also like that he was actually sitting in front of me and he wasn't too far or too close. I think the distance from where he was to me on the screen was helpful, because it was like it was just us two.*

They also felt that the VP, being not too realistic and an animated avatar, made it easier to engage in conversation in a training setting. They added,

> *I'm like, would that actually be scarier for me, because it feels too real? I'll probably be second guessing my responses, whereas here it felt like I was talking to someone my age, and I feel like, maybe that's good.*

On the other hand, P2 mentioned

> *I was more focused on how his eyes were not moving. It kind of gave me the uncanny valley feeling. I think I was so conscious of trying to maintain eye contact, I didn't notice (the body language of the VP).*

Hence, they requested more realism, specifically in the eye movements.

Flow of Conversation With the VP

Although participants found that the pauses were good in giving space for validation and mimicked what a conversation would be like in the field, more interactivity in responses was desired from the VP. P2 felt that the pauses gave them a chance to acknowledge how difficult the conversation was and recognized that people would appreciate the space and pauses for their feelings to be validated. However, P2 highlighted that

> *I couldn't understand some of his responses. I don't know if they were realistic… After I validated him, all he did was grunt. He never actually said it was hard, so I guess I had to be picking up on that, right? But yeah, I think he just didn't interact that much.*

P3 also echoed, "I was really interested in him elaborating more of what he was experiencing, and then reassuring him that it was okay."

Discussion

Overview

Our findings indicate that the AR simulation demonstrated above-average usability, as reflected in PSSUQ scores and corroborated by qualitative accounts of realism, immersion, and empathetic engagement with the VP. Participants perceived the tool as a promising complement to existing training workflows, and the usability data informed a set of design recommendations organized across four domains: environmental context, training structure, VP behavioral realism, and technical hardware considerations (Multimedia Appendix 7).

To our knowledge, this is among the first studies to investigate the potential of using AR, rather than VR or desktop-based simulation, for training lay MH task-sharing workers with VP simulation. The majority of existing simulation research targets credentialed clinicians or nursing students in controlled settings; our study extends this work to community-based task-sharers who provide frontline MH support in underresourced communities [9,10,39-42]. Furthermore, the tool was co-designed through participatory methods with stakeholders from the HSI, ensuring that the training content and interaction design reflect the cultural and contextual realities of the population served [67,68].

Principal Results

Current Challenges in MH Training

Traditional MH training often grapples with challenges in content simplification due to lack of resources [19,20]. Role-playing has often been used as a method to help trainees develop critical skills such as empathy, communication, and problem-solving [87]. While it is an effective way to simulate real-life scenarios and practice responses, it also presents challenges such as ensuring that role-plays are realistic and emotionally safe for participants, thus requiring skilled facilitators and significant preparation [87]. Echoing the literature, participants mentioned role-play in current training mostly being done between peers. Acting out more challenging scenarios, such as schizophrenia symptoms, was difficult to accurately role-play and might even be left out as peers were not trained actors. Current training often did not use trained actors as providers would require resources like time and money which they mostly do not have [88]. Our findings suggest that adding AR to the current workflow could increase more representative and effective role-play training.

Additionally, trainees may have theoretical knowledge but may require more intensive training in more nuanced practical skills such as reflecting on and interpreting people's feelings and responses [89]. Participants emphasized the struggle of adapting theoretical knowledge to practice with current training methods. They expressed that theoretical knowledge is limited in its effectiveness, and they ultimately had to learn the ropes on the job and develop their own style of counseling. In addition, participants expressed difficulty when interpreting qualitative responses, translating them into a quantitative scale, and identifying how to help people due to individual subjectivity, reflecting their adaptability challenges with current traditional

training. Notably, participants found that the AR training simulation allowed them to practice in a safe and comfortable environment where mistakes were acceptable and did not have detrimental consequences.

A systematic review found that racial and ethnic minority populations faced cultural MH stigma, which led to greater barriers to MH services and lack of trust [90]. Building trust between providers and patients in MH services is important to promote and maintain treatment and engagement [91]. Similarly, participants emphasized that building trust with patients was challenging but important. This type of engagement is difficult to train using traditional methods yet crucial for authentic patient relationships.

Enhancing Training Quality

An integrative review found that realism and debrief were important in MH simulation training and improved trainees' engagement and in bridging the gap between theory and practice [92]. Our study's results highlight that the realism of the AR simulation and the quality of the animations led participants to feel empathy and connection toward the VP. Participants emphasized that they felt like they (the VP and participant) were the only ones in the room, indicating that the AR simulation was successful in immersing participants into a real-life scenario of conversing with a community member. The VP's voice had an accent and was realistic, reflecting the population they would be interacting with, further allowing participants to feel like they were talking to a real person and practice communication. The VP's animation and body language allowed trainees to further empathize with the VP and practice building trust. Through MH training simulation with SPs, trainees could gain empathy, compassion, and confidence, benefiting the people they serve [93]. The AR simulation was realistic, immersive, and sparked empathetic connections, thereby allowing trainees an environment to practice engaging and building trust in a realistic and effective manner.

Additionally, participants highlighted that AR simulation can better depict challenging scenarios, especially specific DSM categories like schizophrenia, depression, and anxiety. They emphasized that a standardized role-play training that best accurately depicts symptoms, rather than peers acting out the symptoms, would be extremely useful for practice. As such, having realistic practice in AR before real-life interactions can build provider efficacy and better care for patients. This kind of applied training is crucial for effective care by providers and MH task-sharers, with studies showing that using AR or VR to practice in a safe environment enhances knowledge and transferable skills, leading to the transfer of knowledge and skills in clinical practice [94]. Thus, this AR-assisted training tool could bridge the gap in training accuracy and enrich current traditional role-playing training.

The Role of Realism and Immersion in AR Training

Overview

Studies have shown that higher realism in immersive virtual experiences leads to a more positive user experience, highlighting that degrees of realism affect the extent of immersion and thus the training's effectiveness [95]. When such training elicits emotional responses similar to those experienced in real-life situations, empathy is found to be nurtured in trainees [36]. Thus, it is important to create a realistic training experience for trainees to develop empathy and immerse fully. In this section, the factors that contribute to realism include the VP's body language, voice, distance from the trainee, appearance, eye movements, and dialogue.

Body Language

Nonverbal cues such as facial and body movements have been shown to facilitate connection with VPs [96]. Participants in our study empathized with the VP and wanted to reassure, validate, and comfort the VP when they perceived distress through the VP's body language. We recommend designing VPs with realistic nonverbal cues to enhance immersion and empathy (Multimedia Appendix 7).

Voice

Virtual assets' realism and appropriate contextualization enhance one's perceptual skills, which are essential for developing sensemaking abilities when using AR [97]. Our study's VP had a real person's voice with an accent, and participants pointed out that this was very useful for training their listening skills, especially for specific populations or communities they may be training for. They added that the headset's technical limitation, that led to the soft volume, was actually useful in training them to listen more attentively to soft-spoken people. These findings emphasize that voice realism in the VP is useful and crucial for participants to hone their sensemaking skills in MH training. Using a representative real person's voice and varying volume levels can train attentive listening skills (Multimedia Appendix 7).

Distance From Trainee

The results highlight that the distance of the VP from the participants was realistic enough, not too close or too far, and that this facilitated easier engagement and immersion in the training. This corroborates with literature findings that training systems which are context-specific enhance learning [97]. Placing the VP at a therapeutically informed comfortable distance enhances immersion (Multimedia Appendix 7) [98].

Appearance

Our findings, also supported with literature, suggest that representing the VP as an animated 3D avatar instead of making the VP too human-like helped in avoiding the uncanny valley effect; this is the discomfort or eeriness experienced when digital avatars closely resemble human beings but fall short in certain aspects of realism [99,100]. Balancing avatar realism to avoid the uncanny valley effect is recommended (Multimedia Appendix 7).

Eye Movements

One participant perceived the VP's eyes as staying still, and it reduced their ability to notice body language cues that were programmed into the training module and broke the immersion for them. The perception of the eyes not moving, even though they were programmed to move, contributed to them experiencing the uncanny valley effect. This highlights the importance of making the eye movements more realistic and

obvious to ensure that the uncanny valley effect is minimized and to increase immersion, especially when gaze-tracking is correlated to trainees' assessment skills [97]. Realistic and obvious eye movements are essential for maintaining immersion (Multimedia Appendix 7).

Dialogue

Although pauses in dialogue were good in giving space for validation and mimicked a real conversation in the field, more interactivity in the VP's responses was desired by participants. In addition, one of the participants felt like the responses were lacking in realism; for example, the VP grunting as a response. These findings align with evidence that dynamic, contextually responsive VP dialogue is crucial to perceived realism in simulation-based training [21,97]. More interactive, dynamic VP responses would enhance conversational realism (Multimedia Appendix 7).

Immersion was also affected by the structure of the training. This included the use of prompts, which have been found to be useful for guiding learning [97]. Although the prompts were useful in guiding participants on how to respond when they were unsure, navigating between two types of prompts confused users and reduced immersion. Switching between a general prompt and a specific word-for-word prompt (Figure 7), paying attention to the VP's body language and dialogue, and asking the questions from the PHQ-4 form broke the flow of immersion and caused confusion in participants at times. Clearly distinguishing prompt types and gradually transitioning from guided to unguided interactions would improve training flow (Multimedia Appendix 7).

Overall Usability and Acceptability of AR Tool

Our findings show that the AR-assisted training tool is useful for MH training and has the potential to scale to different MH contexts, especially more complex scenarios. Qualitative results highlight the overwhelming positive sentiments toward the AR tool and its promising potential in successfully filling the gaps of current training workflows. The overall PSSUQ scores indicated above-average usability, consistent with patterns reported in comparable simulation-based training evaluations [92,101]. The interface quality subscale performed particularly well, suggesting that the AR tool's interface met user expectations for functionality and pleasantness, an outcome that aligns with findings that higher-fidelity immersive environments tend to yield stronger user acceptance [36,95]. High reported desire to use the system frequently further supports the tool's acceptability as a complement to existing training workflows.

The main challenges of integrating this tool into the wider MH training community are the technology learning curve and hardware limitations. Two out of the three first-time users of AR and VR headsets experienced difficulty at the start. Although they expressed that they were overwhelmed by all the different things to pay attention to, they also highlighted that with more practice, they would adjust to the training and benefit from it. This is a positive outcome since AR and VR headsets are known to have a steep learning curve [101]. The two participants who raised this concern were in the 35- to 40- and 56- to 60-year-old range, respectively, which may indicate that the older demographic, who tend to have a lower technology learnability rate, could find this AR tool to have a manageable learning curve [102]. We recommend keeping this challenge in mind and working on building a seamless onboarding process when introducing a similar training tool.

Another challenge for integration is the headset's hardware limitations, including the headset falling down due to a missing accessory pack for supporting a range of nose bridges, the headset heating up, and low audibility even on the headset's maximum volume. This was an internal software issue that could be fixed in hindsight. The headset falling down affected the PSSUQ scores, particularly as this discomfort led to breaking participants' immersion. A study using similar AR HMDs also mentioned that issues such as user discomfort and technical limitations of HMDs need to be addressed before widespread adoption in the health care industry [103]. Thus, these challenges must be addressed for a successful implementation of this tool. We recommend addressing hardware fit, comfort, and cost challenges; integrating familiar training workflows; incorporating personalized feedback mechanisms; and enabling VP response replay (Multimedia Appendix 7).

Limitations

This study has several limitations that should be considered when interpreting the findings. First, as an exploratory study, the work reported here involved a limited number of participants, making it difficult to draw generalizable conclusions. Due to the small sample size, a descriptive analysis was used instead of a test of significance. The selection of the "N/A" option affected the quantitative results. To minimize this, an additional instruction could have been given to participants before they filled out the quantitative survey to remind them that if they did not understand the question, they could clarify with researchers. Due to the attrition of one participant (P5) and the small pilot sample size, thematic saturation was not reached; however, the data collected from the remaining four participants provided consistent insights into the tool's usability. This study was intended to understand usability and user perceptions rather than to evaluate training effectiveness or learning outcomes. The promising results indicate the need for future studies, such as collecting quantitative data from a larger sample size and measuring trainees' actual performance after AR-assisted training.

Second, the hardware challenges might have affected the data. Participant satisfaction with AR training has been shown to vary depending on technical factors [104]. Comfort issues such as overheating from low battery life, accommodating glasses wearers (which caused a participant to drop out of the usability test), and the lack of an adaptive fit for certain nose bridges and head sizes could not be overlooked. The hardware costs also presented challenges for the scalability of being widely used in the community.

Third, the study was conducted in a single site; hence, our results may lack transferability to other settings with different parameters, which is an especially important factor to consider for educational learning interventions [105]. The investigation was also context-specific, which may not be generalizable to screening for other MH conditions. Using more in-depth scales

to test realism and immersion and the relationship it has with effectiveness in a different experiment would also further enhance this study.

Conclusions

This pilot study provides promising preliminary evidence that AR-based VP simulation is a usable and engaging training modality for MH task-sharers. The study is among the first to apply AR glasses with VP simulation to this population, filling the gaps of past studies that have predominantly used VR or desktop-based systems with credentialed clinicians and nursing students. This pilot study brings preliminary empirical usability evidence from a validated instrument (PSSUQ) demonstrating above-average usability, and a set of interaction design recommendations spanning environmental context, training structure, VP behavioral realism, and technical hardware considerations. These findings show promising results that AR-based simulation could enable MH task-sharers in underresourced community settings to access realistic, culturally tailored training practice at a lower financial, labor, and time cost, directly addressing the resource constraints of current training approaches. Future research should explore cost-effective hardware alternatives that address comfort and accessibility challenges, increase sample sizes for inferential analysis, compare AR-assisted training simulations with traditional methods, and extend the tool to additional MH conditions for greater generalizability and scalability.

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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].

Conflicts of Interest

None declared.

Multimedia Appendix 1
ARATT demo.
[MP4 File, 47020 KB - xr_v3i1e80711_app1.mp4]

Multimedia Appendix 2
Screening Scenario script.
[PDF File, 24 KB - xr_v3i1e80711_app2.pdf]

Multimedia Appendix 3
Semistructured interview questions.
[PDF File, 44 KB - xr_v3i1e80711_app3.pdf]

Multimedia Appendix 4
Qualtrics questionnaire.
[PDF File, 197 KB - xr_v3i1e80711_app4.pdf]

Multimedia Appendix 5
Summary of key themes.
[PDF File, 76 KB - xr_v3i1e80711_app5.pdf]

Multimedia Appendix 6
Quantitative responses table.
[PDF File, 39 KB - xr_v3i1e80711_app6.pdf]

Multimedia Appendix 7
Summary of design recommendations.
[PDF File, 80 KB - xr_v3i1e80711_app7.pdf]

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Abbreviations

APA: American Psychiatric Association
AR: augmented reality
CIMH: Center for Innovation in Mental Health
DSM: *Diagnostic and Statistical Manual of Mental Disorders*
HMD: head-mounted display
HSI: Harlem Strong Initiative
INFOQUAL: information quality
INTERQUAL: interface quality
MH: mental health
MR: mixed reality
NDA: National Institute of Mental Health Data Archive
PHQ-4: Patient Health Questionnaire-4
PSSUQ: Post-Study System Usability Questionnaire
SP: standardized patient
SYSUSE: system usefulness
VP: virtual patient
VR: virtual reality

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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

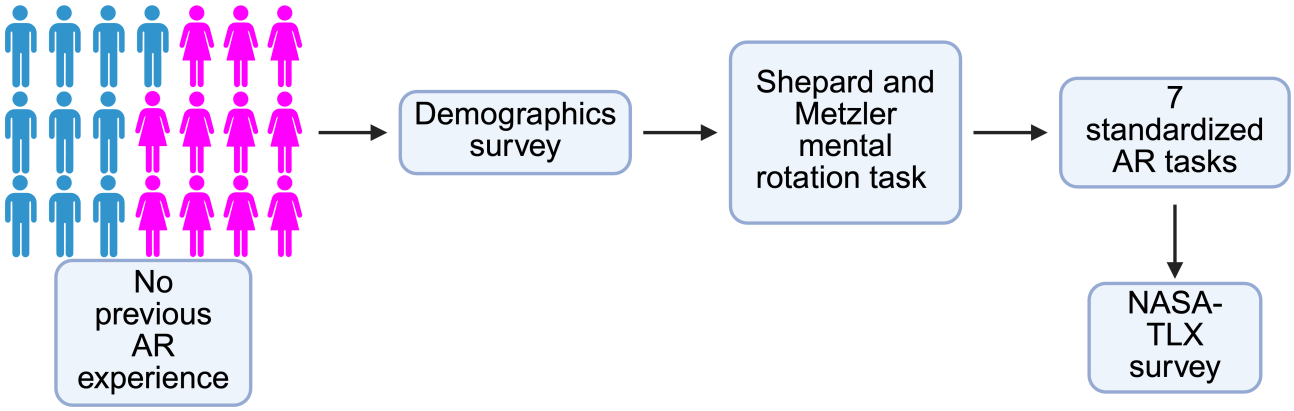
Participants comprised undergraduate, graduate, and medical students at the University of Pittsburgh between June 2024 and December 2024. Participants who had previous experience using AR were excluded.

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].

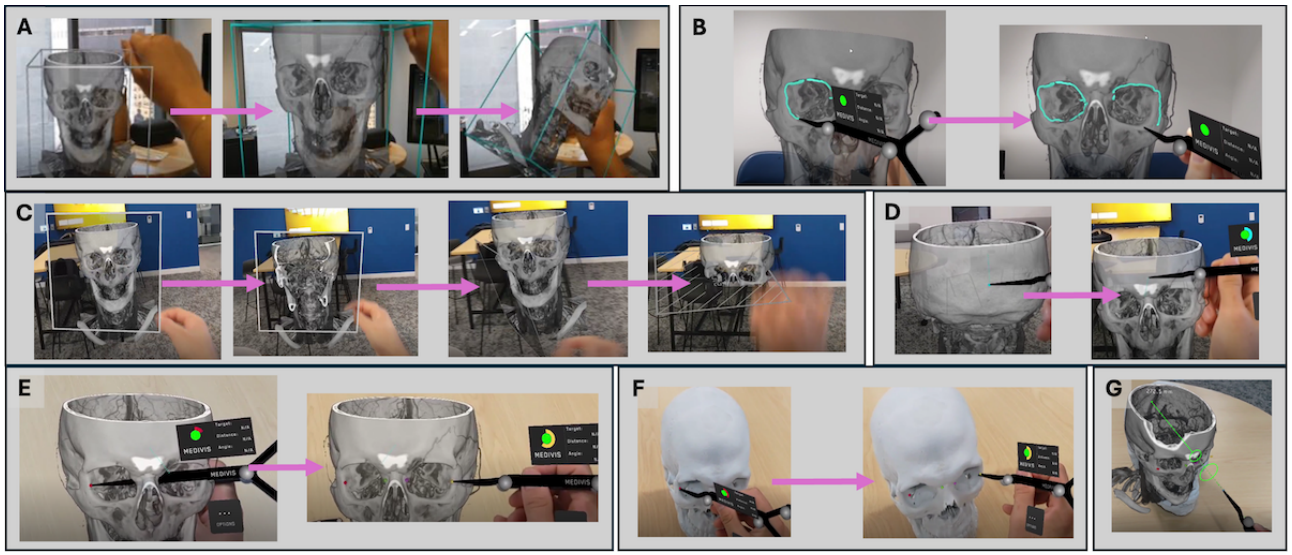
Experimental Procedure

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.

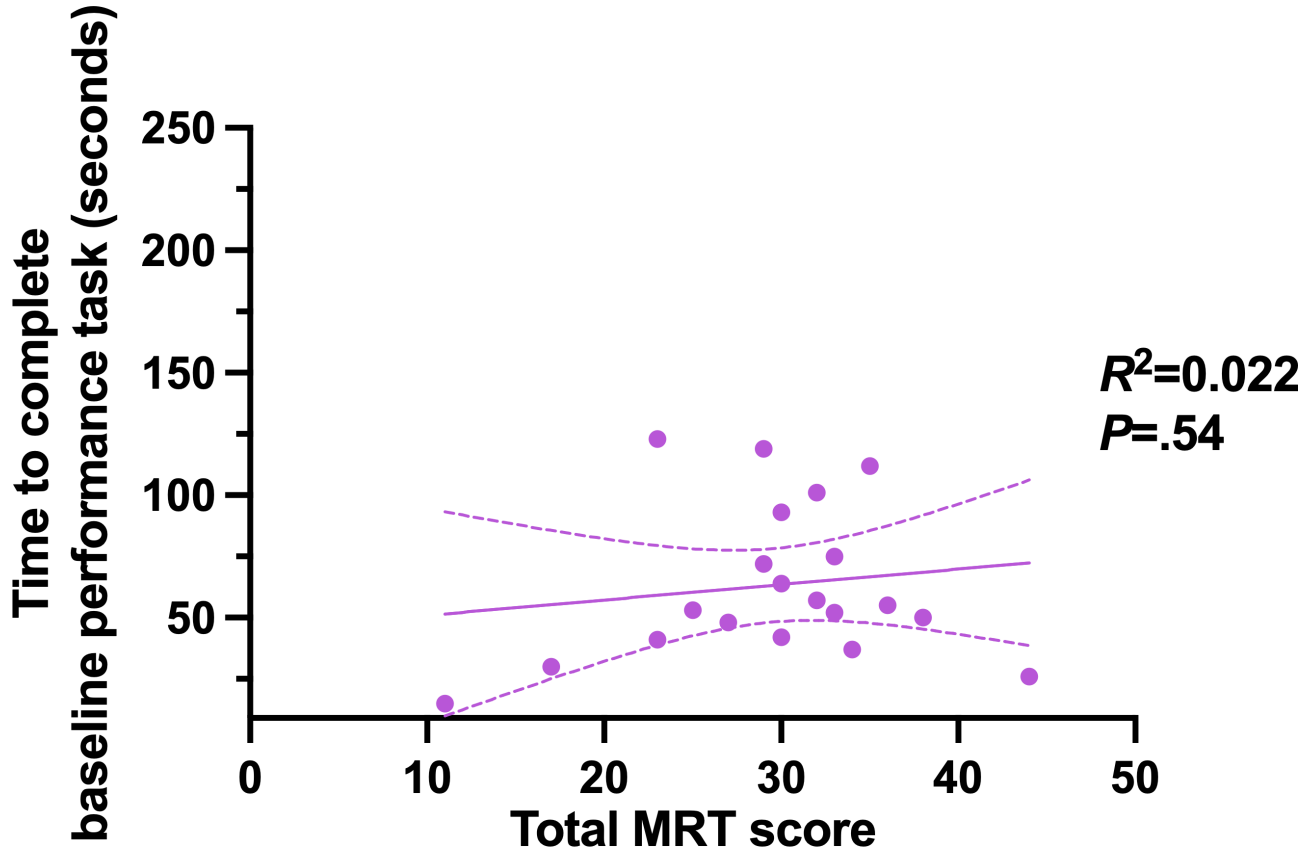
Table . National Aeronautics and Space Administration Task Load Index scores.

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

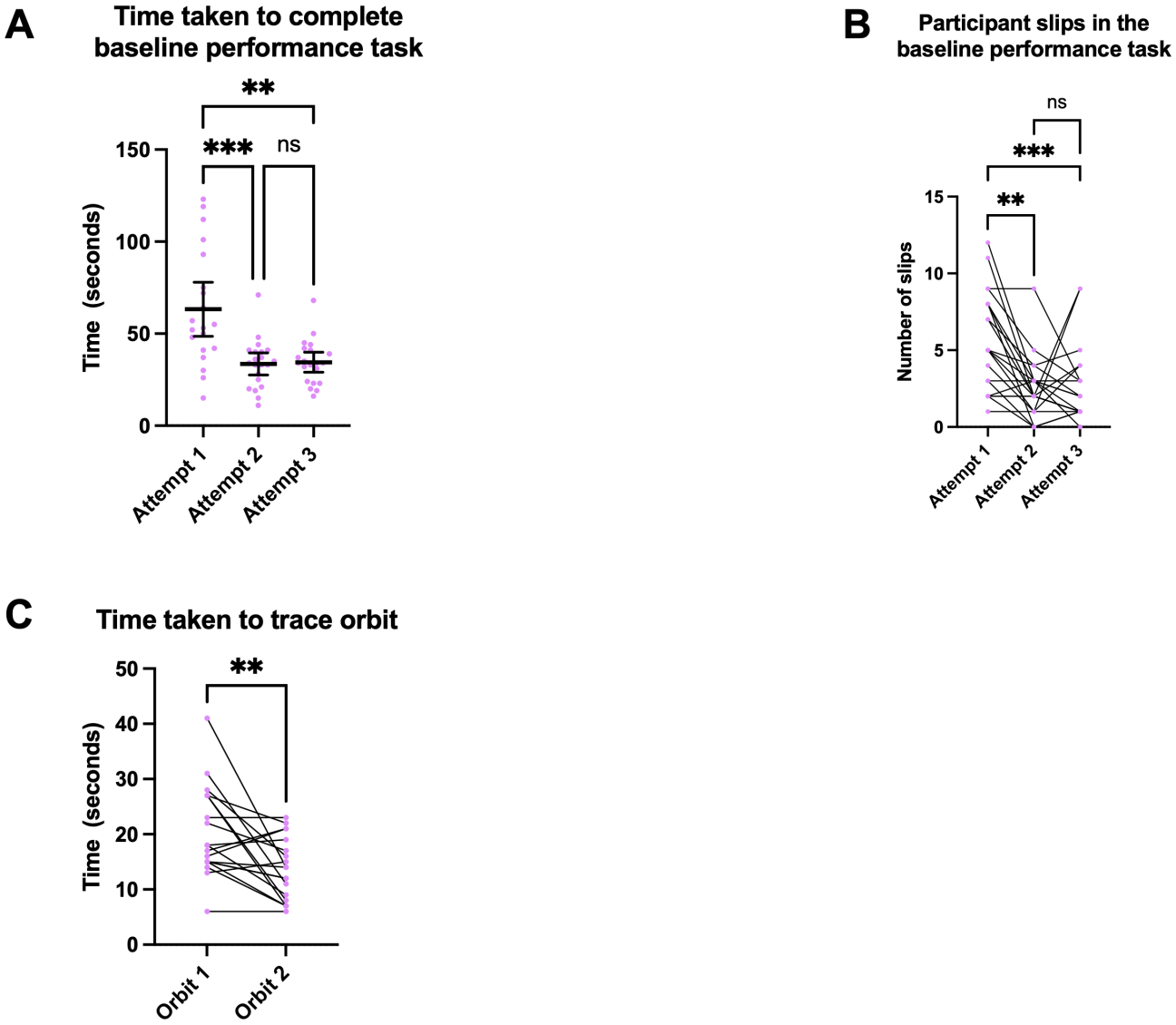
Participants were split into 2 groups based on video game experience (group with "extensive" experience of >5 hours/week and group with "minimal" experience of ≤5 hours/week) for analysis. This distribution was determined empirically to yield approximately equal participants per group (8 and 13, respectively). 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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Virtual Reality in Health Professions Education: Qualitative Descriptive Study of Educators' Perspectives

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Abstract

Background: As virtual reality (VR) technology has become more accessible, the potential of this technology has been increasingly investigated in higher education institutions to improve teaching and learning. While VR can provide immersive experiences to support visualization and active learning, its adoption in health professions education is often limited by high costs, technical complexity, and a lack of pedagogical fit. Furthermore, the educator, who is critical to curriculum design, is underrepresented in the discourse on VR integration, especially in resource-constrained environments in South Africa.

Objective: The purpose of this study was to investigate the perceptions of health professions educators regarding the potential value of immersive VR in the educational process, the implementation barriers, and the requirements for successful curriculum integration at a South African university.

Methods: A qualitative exploratory descriptive design was used. Eighteen educators (N=18) from a wide variety of health disciplines (including physiotherapy, occupational therapy, nursing, and dentistry) were recruited from the Faculty of Community and Health Sciences. Participants interacted with 3 immersive VR applications (The Body VR, Sharecare You VR, and Wraith VR), which were chosen to represent varying levels of clinical complexity. Semistructured interviews were used to explore their perceptions. Data were analyzed using reflexive thematic analysis in accordance with the framework of Braun and Clarke. Sample size adequacy was determined using information power.

Results: Five overall themes were constructed from the data: (1) the experience of VR, where educators enjoyed the engagement but initially felt that VR was a "gaming" novelty; (2) teaching and learning preferences, where VR was considered a potential tool for authentic and individualized learning; (3) challenges of VR, where issues of visual overload, cybersickness, and logistical barriers were reported; (4) clinical competency and patient safety, where VR was valued as a safe space to manage errors; and (5) curriculum integration, where there was a preference for scaffolding the use of VR from foundational anatomy in the junior years to procedural simulation.

Conclusions: Educators have a favorable view of VR as a powerful supplemental tool that can help boost student engagement and bridge the gap between theory and clinical practice. However, successful implementation involves more than purchasing hardware; it requires a strategic "scaffolded integration" approach that ensures VR applications align with specific curricular outcomes. It is the role of institutions to not only provide technical assistance but also pedagogical training and support for infrastructure to transform a technological gimmick into an ongoing educational resource.

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KEYWORDS

virtual reality; VR; teaching and learning; educators; teachers; health professions education; medical education; technology education; technology-enhanced learning; TEL; education; experiences; attitudes; perspectives; immersive

Introduction

Background

Virtual reality (VR) technology is no longer restricted to the gaming industry; it has entered the classroom as a pedagogical tool in health professions education (HPE) [1]. This step has provided learners with an immersive environment that can facilitate visualization of complex anatomical structures, which cannot be easily created physically without causing patient harm [2]. Extensive evidence exists that VR is useful in facilitating learning, spatial awareness, and motivation [3-6]. However, as the hype around the technology wears off, the question has moved past whether it will work to how we keep it going. This is particularly vital in resource-constrained settings, where implementing new technology can be a challenge amid other priorities within the education system [7].

Even though VR was initially promoted as a low-cost alternative to high-fidelity simulation-based learning (SBL) techniques that require expensive mannequins, consumables, and separate rooms, it does not replace any training tool. The finances are delicate [8-11]. VR involves a high initial cost for equipment, software, and technical support [12]. According to Ravichandran and Mahapatra [12], the initial expenses are high, but VR can be scaled in the long run; once the app is purchased, many thousands of students can use it at a very minimal incremental cost compared to the current expenses of cadaveric dissection or wet laboratories.

Although VR has been cited as having advantages over other pedagogical techniques, including SBL, it also presents realistic challenges in HPE. Two recent studies conducted by Nemani [13] and Soltani and Rostami [14] emphasize that successful integration is often hindered not only by hardware limitations and constraints but also by institutional and organizational constraints, including people (human resources). Furthermore, the exploration of “educator readiness” is required. Educators are the key gatekeepers of the curriculum. If they view VR as a “gimmick” or lack the pedagogical competency to integrate the technology, there is a risk of marginalizing it as a supplementary activity rather than a core learning modality.

This challenge is more pronounced in developing countries such as South Africa, where, due to the digital divide and infrastructural constraints, the use of immersive technologies can be a daunting prospect [15]. Mondal and Mondal [16] noted that to prevent the waste of technology, a detailed alignment with the local curriculum is required. However, educators’ voices on the use of VR are underrepresented in the global literature and are predominantly biased toward high-income nations [17]. Understanding how educators in South Africa view the pedagogical value, ease of use, and logistical overhead of VR is imperative for developing implementation strategies that are culturally and institutionally sustainable.

Therefore, the purpose of this study was to explore the perceptions of health professions educators at a South African university regarding the immersion of VR. Furthermore, the identification of potential pedagogical challenges (such as implementation) and possible solutions and strategies was explored.

Purpose of the Study

Health professions educators are among the key stakeholders in incorporating VR into the curriculum. Therefore, exploring educators’ perspectives on the use of VR is fundamental to the sustainable integration of VR in HPE. Thus, this study seeks to understand educators’ perceptions of VR in HPE, with special reference to perceived educational value, implementation difficulties, and issues in curriculum integration.

Methods

Study Design and Setting

This study used a qualitative, exploratory, and descriptive design within an interpretivist paradigm. This approach was chosen to bring out participants’ lived experiences as health professions educators as they interacted with novel VR technologies, thereby allowing for a rich, context-dependent understanding of their pedagogical perceptions [18,19]. The study was conducted in the Faculty of Community and Health Sciences at one of the research-intensive universities in the Western Cape, South Africa. It was an interdisciplinary setting that encompassed physiotherapy, occupational therapy, nursing, psychology, and dentistry, among other educational areas within the health sciences.

Participant Selection and Recruitment

Academic employees were selected through purposive sampling to ensure that they were actively engaged in teaching at the Faculty of Community and Health Sciences. Advertisements for recruitment were sent via email to the faculty and distributed at department meetings. To secure a wide range of opinions, maximum variation methods were used to select participants from various disciplines with different degrees of teaching experience (junior lecturers, lecturers, senior lecturers, and associate professors) and different levels of technology experience (junior or experienced). Participant recruitment continued until a certain level of information power was achieved [3]. The continuous recruitment ensured adequate specificity and depth to achieve the study’s goals and objectives, and 18 participants were recruited.

VR Intervention and Procedure

All participants were taken through a structured VR workshop prior to the interviews to establish a baseline of experiential knowledge. The lessons were conducted in a special simulation laboratory with HTC VIVE Cosmos VR goggles. The participants were requested to experience 3 particular VR applications, which were selected to illustrate different pedagogical affordances:

1. The Body VR: a narrative storytelling journey that takes the user within the bloodstream, via an immersive approach, throughout the body. The application is designed to illustrate abstract physiological concepts (key characteristics and components: passive and observational).

2. Sharecare You VR: a highly interactive anatomical atlas allowing for the dissection and manipulation of organs (key characteristics and components: active and exploratory).
3. Wraith VR: a procedural simulation requiring manual dexterity and sequence recall (key characteristics and components: active and procedural).

Each session lasted about 20 to 30 minutes, and participants were given time to familiarize themselves with the hardware and interface before reflecting on the experience.

More details on the VR application are provided in Multimedia Appendix 1.

Data Collection

Data were collected via semistructured individual interviews immediately after VR exposure (Multimedia Appendix 2). The semistructured interview guide was developed using the CAMIL (Cognitive Affective Model of Immersive Learning) framework [20]. Makransky and Petersen [20] framework provides a grounded basis for identifying key constructs relevant to the learning context, including interest, motivation, embodiment, and self-regulation. Although the thematic analysis was conducted using the reflexive thematic analysis (RTA) inductive approach, without using CAMIL as an a priori coding framework, it allowed themes and subthemes to emerge from the interviews rather than from existing theory and literature. The primary focus of the interviews revolved around the following:

1. Pedagogical affordances: What are the key components you think are needed for a successful VR integration in the educational system?
2. Implementation barriers: What is hindering the ease of using VR?
3. Curricular alignment: In which module will you implement them (describe how the module is able to link to VR)?

Interviews were audio-recorded with participants' consent. The primary researcher wrote field notes and reflexive memos throughout the data collection process to document nonverbal cues and early analytical thoughts.

Data Analysis

Thematic Analysis

The data analyzed utilized the RTA approach, as outlined by Braun and Clarke [21]. This was an iterative 6-phase process that involved the following:

1. Familiarization: repetitive listening to audio recordings and reading transcripts in order to immerse oneself in the data.
2. Coding: sequential production of systematic semantic codes and latent codes for the entire dataset.
3. Generating themes: pulling together codes into possible themes that represent shared patterns of meaning.
4. Reviewing themes: reviewing themes against the coded extracts and the overall dataset to ensure that they create a coherent narrative.
5. Defining and naming themes: developing the details of each theme to make them clear and distinct.
6. Writing up: writing the final report.

The Role of Artificial Intelligence in Data Analysis

After the primary researcher completed the initial analysis, the artificial intelligence (AI) model was provided with the human-developed codebook and the anonymous semistructured interview transcript for analysis. The initial prompt involved giving the AI model a role; the research aim, objective, and research question were provided (eg, "You're a Professor at a University working in the Physiotherapy Department"). The AI model was instructed to identify excerpts that differed from or codes that contradicted the researchers' primary findings. The results from the AI model were treated as unverified notes, and gaps were identified; they were cross-referenced by the research team against the raw audio and transcript to ensure contextual accuracy and truthfulness. The final decision on the results was determined by the researchers.

Trustworthiness and Rigor

Rigor was established by using the criteria of credibility, transferability, dependability, and confirmability [22].

- Credibility: ensured by spending time with the data and researcher reflexivity. The researchers scheduled quarterly meetings with an institutional researcher to discuss, debrief, and provide feedback and questions about the study's analysis process.
- Transferability: enhanced through the provision of detailed descriptions of the study setting, participants, and the VR intervention to enable the reader to judge whether they might apply to other contexts.
- Dependability and confirmability: an audit trail was maintained for key methodological decisions, including the development of a codebook, subthemes, and themes.

Reflexive Statement

The lead researcher is a physiotherapy lecturer working in the same faculty as all participants, with an understanding of the educational environment and potential biases. A desire to deploy VR in health sciences education, driven by a disciplinary background as a physiotherapist, was recognized at the outset as likely to affect coding and interpretation processes. This was moderated through reflexive memos during data collection and analysis processes to expose and challenge underlying biases. Regular supervisors' meetings helped to externalize thinking. Participants were encouraged to know that both critical and positive responses were sought and valued. During the interviews, participants were reminded of the lead researcher's role. A semistructured interview was used to allow participants to elaborate on their experiences and perceptions rather than simply responding to an investigative prompt.

Ethical Considerations

Ethics approval was granted by the Humanities and Social Sciences Research Ethics Committee of the University of the Western Cape (reference HS22/6/55). An information sheet and a consent form were sent prior to the interviews, and the participants signed the consent form before starting the interview process. All identifiable information was removed from the transcript before data analysis. To protect data privacy during AI processing, only deidentified textual data were input into

ChatGPT. Participants in this study did not receive any stipend or compensation.

Results

Demographics and Background

The participants' ages ranged from 32 to 54 years, with a mean age of 42 (SD 9.44) years. Occupational therapy, physiotherapy, dentistry, nursing, psychology, social work, sport, recreation and exercise science, biokinetics, and the Interprofessional Education Unit were represented. Details of the participants are available in Multimedia Appendix 3.

Themes, Subthemes, and Codes

The analytical process involved the creation of 105 initial codes, inductively developed from the interview data and field notes (Multimedia Appendix 4). These codes represented fragmented ideas, experiences, and perceptions expressed by participants and remained data-driven during initial familiarization and the initial round of coding. Through an iterative and reflexive process, the codes were compared, sorted, and refined to highlight patterns of meaning. Similar codes were then organized into 16 subthemes that captured common pedagogical, experiential, and contextual issues from participants' experiences. These subthemes were grouped into 5 high-level themes that captured higher-level patterns of meaning related to educators' views on VR in HPE. Themes were developed based on analytic consistency and interpretative meaning rather than on counts, as is typically the case in RTA. Consultation between the authors on codes, subthemes, and themes was ongoing throughout the data analysis to ensure the representativeness and fit of the codes and themes. This also enabled them to be defined and redefined through data analysis.

The Educator's Experience in the Use of VR

Before this study, most participants had only heard of or had a surface-level understanding of VR terminology. Some participants had VR experiences related to watching media or videos on their phones. Participant 14, a dentist, said, "Nothing was done before, not even a VR video." This sentiment was echoed by participant 3, a physiotherapist, who noted the transition from gaming to education: "Gaming, I've mostly seen it in gaming and gradually… [they are] trying to bring it into the teaching environment as well." For many of these professionals, the research project provided their first physical encounter with fully immersive virtual worlds. It is important to note that the interview questions addressed VR in general, but the participants' responses were heavily influenced by the high-fidelity, fully immersive experiences provided during the study.

The emotional reaction to this was largely positive, even though there was no prior experience, and it was defined by an emotional wow factor. The most frequently used words by the participants to describe their participation were immersion, excitement, and fun. Indicatively, a psychologist, participant 5, reported feeling deeply emotional about the experience of cellular visualization: "I felt like I was inside the cell. I was struck. I adjusted the wow factor to that. Wow. What is it? I have never experienced anything of the kind; therefore, in my case, it was the first time that I was exposed to the virtual environment." This feeling of belonging to the setting is a characteristic feature of high-presence VR and represents a major change from traditional classroom observation. Participant 3 (physio) pointed out the direct influence of these affective factors in the learning process: "It feels more fun, more fun. It is more immersive, and as I listen to the models, I can see their labels and look around to see where these models or structures fit." This participant also mentioned that this would be more interactive for students; it is more fun, suggesting that the fun of the VR experience might be an effective motivator for student engagement.

Teaching and Learning Preferences

The participants found VR to be a powerful alternative modality that can add value to education through its immersive, interactive nature. Instead of being a passive visual representation, the technology was viewed as a stimulus for various learning orientations, such as exploratory, active, and individualized learning.

Immersive Learning

The ability to immerse oneself in the content deeply, the feeling of being physically present, was considered to be one of the main motivators of retention. Participant 7 (sport science) claimed that the value of VR lies in its ability to aid memory through active participation: "The one value is that it helps you to remember. As you are part of what you are learning." This experiential "being part of" the content facilitates deep encoding and retrieval, as the student is not just observing a process but living it. Participant 9 (sport science) emphasized the importance of spatial perspective in developing clinical insight: "By seeing what happened from a difficult angle, it can help you understand [the condition] after a client has had surgery." This ability to manipulate viewpoints and observe clinical conditions from angles inaccessible in conventional environments provides a deeper level of understanding.

Active and Individualized Learning

Educators stressed the transition from passive receiving to active agency. Participant 7 (ERES) noted the importance of student autonomy: "The fact that you can choose your options, you can go back and choose which part of the body you can do the tests, see where the breakages are, how things are changing and flowing. That makes you feel like you're part of the lesson that's happening, and not just someone who's receiving the old ways of teaching." This sense of participation shifts the student's role from a consumer of information to an active investigator. Participant 15 (dentist) reflected on their own learning style and how VR might have aided their studies: "The type of student I was, and I am currently seeking help with my studying. If I can visualize it, it stays in my memory, as opposed to me going to a lecture, listening and then going home." This highlights the technology's ability to cater to those who struggle with traditional lecture-based formats. Participant 8 (ERES) observed that "It gives the opportunity for the student who learns slightly slower. I'm thinking of individualizing learning. It is almost custom-made for each student. It's like apps on your phone. I could decide how fast we are moving." This customization

addresses the diverse needs of learners and enables a more inclusive educational experience, much as specialized programs can help diverse groups express themselves creatively and overcome repressed emotions.

Authentic Learning

Lastly, the participants discussed the possibility of simulating near-real clinical situations. Participant 14 (dentist) stated, "Ultimately, we would like to strive for authentic learning experiences, and VR could offer that based on the setup scenario." This can be achieved through VR, which serves as a safe, high-fidelity simulation of a clinical setting or a virtual human body.

Clinical Competencies and Patient Safety

One recurring issue among educators was the risk of student errors in the real-world clinical environment. The participants often placed VR as a necessary, nonthreatening intermediate through which it is possible to experience safe failure. Participant 7 (sport science) found value in the nonthreatening nature of the technology: "I could make mistakes. But I felt it was nonthreatening, which is definitely a good thing." Participant 6 (social work) pointed to the moral necessity: "Even if the students make a mistake...they realize they learn from making mistakes. However, in the real environment, it is not possible, as you realize the patient might die." This concept is transformative for clinical training, as it allows students to learn from mistakes that would be unacceptable in a real-world setting.

Students with this safety affordance were directly associated with preclinical preparation and the number of hours of clinical experience. Participant 2 (physio) stated, "VR will improve the student's confidence. More so, to promote and enhance their experiences during clinical placements. Because students would develop competence prior to working with real patients." This is supported by the fact that VR can accelerate skill acquisition and enhance overall clinical outcomes. Educators also regarded VR as a means of overcoming institutional barriers, including limited access to hospitals. Participant 8 (sport science) observed that VR could be used when students "cannot go into hospital settings," as it can "bring the clinical environment to the students" and expose them to complex equipment: "You're placing them in a [virtual] hospital room where they can see all the valves or machines we use in physio; whatever it is, they'll be able to see it." Participant 12 (physio) even proposed a formal recognition of virtual training: "So you could allocate clinical hours as well, not only when they are on block to prepare but also to give them that clinical experience and confidence." Participant 10 (sport science) suggested that "the students' confidence and also the patient [functional] outcome increases, maybe it will even increase students' [clinical] competence." This highlights a shift toward accepting virtual simulation as a legitimate part of professional clinical hours.

VR and Curriculum Alignment

Participants stressed that VR's effectiveness depends on its scaffolded integration into the curriculum rather than its use as a generic add-on. Discipline-specific alignment, in which content aligns with the anticipated outcomes of a particular module, was very popular. For example, the participants proposed that anatomical applications are most appropriate in junior years (first and second years), whereas procedural simulations (eg, Wraith VR) should be used with senior students (third and fourth years) or postgraduate students. Participant 10 (sports science) observed that VR might familiarize junior students before they are expected to perform complex tasks, including the first surgical extraction.

Participants' opinions on the level of integration were inconclusive. Some, such as participants 6 (social work) and 8 (ERE), said they would like VR to become a primary teaching tool, possibly replacing traditional lectures. Others, such as participant 3 (physio), noted that "Theory and textbooks, they do have their place. And I think VR can supplement." However, participant 10 (sport science) suggested an "equal" balance: "I think it will be equal. I would use that equal...I would send them the theoretical information before the time. Then, the main tool is to put it into practice, because that is my work, applying it." This variety of opinions suggests that the optimal level of integration may vary across disciplines and specific learning objectives. Irrespective of the level of use, teachers such as participant 8 (ERES) stated that "the technology should be linked to an outcome module," and that, without understanding the pedagogical fit, the implementation process will be unsuccessful.

Challenges of VR Implementation

The enthusiasm notwithstanding, a number of challenges at different levels were identified, the main ones being cognitive load, cybersickness, technical, logistical, and financial obstacles.

The first problem identified was the risk of visual and mental overload. While powerful visualizations are a strength of VR, they can also be overwhelming for those not accustomed to the stimulus. Participant 11 (ERES) cautioned, "It might be too overwhelming with the visual and hearing all information, all at once, for initial exposure might be a little bit too much if that's their first exposure to content." Participant 6 (social work) noted that this stimulus is not suitable for everyone: "This would be beneficial for those who need this kind of [visual] stimulus, and then you have the other side of the spectrum where it would be overwhelming for those who do not."

There were also complaints of physical discomfort and usability issues. Physical discomfort, specifically "cybersickness," was reported. Participant 4 (psychologist) described a loss of balance: "I lost a bit of balance. And my knees suddenly became weak." Participant 2 (physio) experienced visual issues: "At times, it got a bit blurry and then cleared up. And there were lags." These physiological responses are common in early-stage VR adoption and highlight the need for sessions of appropriate duration and high-quality hardware to minimize vestibular conflict.

Technical obstacles, including the difficulty of controller buttons, served as a major distraction from the learning objectives. Participant 4 (psychologist) noted that "The buttons on the controller were difficult to use; it was complicated." Participant 14 (dentist) found that the interface interfered with the learning objectives: "The biggest distraction for me is that if I pressed the button, I was either too high or too low on the

wrong side." Participant 2 (physio) also observed that "managing the material, my hands with the controls took a bit of practice." These findings suggest that the user interface must be intuitive to prevent the technology itself from becoming a barrier to learning.

Lastly, institutional obstacles such as cost and scalability were raised. Participant 6 (social work) questioned the university's ability to invest: "We're talking about thousands of rands. I don't know if the university has money to invest." The high cost of headsets and software licenses makes scalability difficult. Participant 4 (psychologist) pointed out that "We need to have more than one, or five for the number of students that we have, for it to be valuable."

Class size is a major logistical hurdle. Participants 3 (physio) and 15 (dentist) asked "A class of 75 - 80 students, how long will it take them to rotate one machine?" This rotation time can be a significant drain on teaching resources and limit the time each student can spend in the virtual environment. For VR to be truly effective in a large-class setting, multiple devices and efficient scheduling are required. The challenge of managing limited resources while providing a high-quality experience is a common theme in fields undergoing professional development.

Discussion

Principal Findings

Our study asked health professions educators for their perceptions after using immersive VR to teach certain courses or modules. The study found that educators perceive VR as an educational tool that motivates students, helps them understand complex concepts, and encourages active learning. Other studies have also found that VR is more motivating and can help students understand spaces and engage in active learning [3-6].

Participants in this study indicated that VR will be useful only when aligned with the course and pedagogy. Participants suggested that VR should be employed as part of a lesson aligned with the Course Intended Learning Outcome, rather than simply for "using" technology in teaching. This approach reinforces the importance of alignment and provides the educator and students with a clear aim and learning goal. As with any technology implementation, the initial attractiveness and novelty will maintain students' attention; however, for long-term educational value, sustainability and support are required [23]. These supports are provided by different levels of the institution. For example, a lab technician (manpower) and storage space (infrastructure) are required [24].

Participants, as educators, highlighted that VR is useful for learning from mistakes without risk to the patient, thus creating a safe environment for students to explore and be unsuccessful without causing actual harm to the patient. A safe learning environment is important for students, as it helps them construct knowledge from the provided content [25]. Besides a safe learning environment, it is important for students to learn from their mistakes [26]. VR can provide immediate feedback to help students review their mistakes and learn from them. Additionally, VR offers high replayability, enabling students to return to the virtual environment and redo the learning activity until the desired outcome is achieved.

Comparison With Prior Work

The high expectations individuals have regarding their affective reactions align with earlier research findings, indicating that immersive VR can positively influence engagement and motivation [4,6]. This is in line with larger trends in the adoption of educational technology, in which emerging tools tend to initially produce a surge of excitement before plateauing into more lasting and meaningful applications [27]. However, this paper provides some sense of the impact of novelty by demonstrating that teachers are aware of it and emphasize the necessity of lasting pedagogical value.

Findings can also be interpreted using the CAMIL [20], particularly regarding the constructs of interest, motivation, embodiment, and self-regulation. The descriptions of immersion, interaction, and a deeper understanding of the space provided by participants indicate the embodiment pathway proposed by CAMIL, in which learners experience the virtual environment and think more profoundly. In the meantime, this paper also illuminates important issues such as cognitive load and usability. The respondents reported visual overload and difficulty navigating the VR interface, particularly at the beginning. Even though CAMIL also acknowledges the influence of cognitive load in the context of immersion, these findings suggest that the extraneous cognitive load may also be driven by a lack of experience with the corresponding technology. This confirms the importance of preparatory measures, such as orientation or pretraining, that can enhance usability and reduce mental load [28].

The focus on curriculum alignment and scaffolded integration can be viewed as a valuable addition to the literature. Although the literature shows that VR is effective in enhancing learning outcomes [5,6], very few studies have examined how VR should be integrated into learning programs. The respondents in this research reported a progressive format in which VR implementation must be introduced in basic subjects, that is, anatomy, during the early years, and its application in more complex simulations of procedures during the later stages. This is consistent with competency-based education systems such as the South African National Qualifications Framework (SANQF) [29], which focus on developmental advancement and conformity with professional skills.

The perceived value of VR as a safe environment for practice and error aligns with the SBL literature [30,31]. Nonetheless, teachers in the present research considered VR as a complement, not a replacement, for conventional teaching and simulation techniques. Although VR has its benefits in terms of scalability and accessibility [12,32], its weaknesses include the lack of haptic feedback, which may limit its ability to substitute for hands-on clinical training.

Lastly, the barriers identified in this study, such as cost, infrastructure, and technical complexity, are similar to those reported in past studies [13,16]. However, this study also highlights that these issues are not only technical but also involve institutional readiness and teachers' abilities, which

justifies the need to examine them holistically for implementation.

Future Directions

The future directions of research in VR are as follows:

1. Future research should focus on longitudinal and experimental studies, as this will provide stronger evidence of VR's effectiveness relative to traditional and blended learning paradigms. The perceived effect of VR on learning, skills, and patient safety has been determined [33-35].
2. Further research could explore a design principle or a set of instructions for integrating VR into the curriculum, given the importance of aligning the learning outcomes with the VR application.
3. From an implementation standpoint, research should be conducted to explore scalable, cost-effective delivery models for integrating VR, especially in low-resource environments. This may involve alternative VR delivery options, such as desktop or mobile platforms, as well as other infrastructure models.
4. Finally, there is a need for future research on integration at the curriculum level, exploring the methodical integration of VR into HPE curricula and mapping it to competency frameworks. This work is critical to support the progression from VR as an innovative tool to VR as an embedded tool in HPE.

Limitations

There are several limitations to consider.

1. To begin with, this research was conducted at a single institution and used a small sample (N=18), which may limit the generalizability of the results to other geographical or institutional settings. Nevertheless, the concept of information power, in which sample adequacy is judged by the relevance and richness of the information in relation to the study aim, was used to assess sample adequacy. In this study, the specificity of the educator sample and the thoroughness of the RTA indicated that the data held sufficient information power to support meaningful interpretation. In addition, participants' years of experience were not collected, even though this could have informed their curriculum and VR-teaching practices.
2. The perceptions were gathered after a brief demonstration; therefore, the responses could also have been influenced by novelty bias rather than by long-term pedagogical usefulness.
3. This research did not measure learning outcomes; although perceptions provide a clear picture of feasibility, further research is needed to quantify objective skills acquisition.
4. Since only 3 applications were shown, the results might not be representative of the overall capabilities of more sophisticated or custom VR systems that are under development.

Conclusion

To sum up, health professions educators view VR as an engaging and potentially disruptive learning tool when designed structurally in line with educational objectives. Although VR offers distinct benefits in motivation, immersion, and scalability, it should be used as a strategic addition to current teaching and simulation techniques. The key to successful implementation in resource-constrained settings lies in shifting the current trend of momentary enthusiasm toward a systematic examination of curricular constraints and intended evaluation methods. VR has great potential to enhance the quality and safety of HPE by addressing institutional barriers and offering pedagogical support.

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Data Availability

The datasets generated and analyzed during this study are not publicly available due to the privacy of the participants (university staff) but are available from the corresponding author upon reasonable request.

Authors' Contributions

All authors have contributed to the study. TWY was the primary investigator and conducted the study, analysis, and manuscript writing. MR and JF contributed to the conceptualization, methodology development, project supervision, and writing (review and editing).

Conflicts of Interest

None declared.

Multimedia Appendix 1

Virtual reality application details.
[DOCX File, 3642 KB - xr_v3i1e52925_app1.docx]

Multimedia Appendix 2
Semistructured interview guide.
[DOCX File, 3644 KB - xr_v3i1e52925_app2.docx]

Multimedia Appendix 3
Faculty of Community and Health Science.
[DOCX File, 3647 KB - xr_v3i1e52925_app3.docx]

Multimedia Appendix 4
Themes, subthemes, and codes.
[DOCX File, 3648 KB - xr_v3i1e52925_app4.docx]

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Abbreviations

AI: artificial intelligence
CAMIL: Cognitive Affective Model of Immersive Learning
HPE: health professions education
RTA: reflexive thematic analysis
SANQF: South African National Qualifications Framework
SBL: simulation-based learning
VR: virtual reality

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Evaluating the Effects of Clinician Prescribing and Implementation Materials on Adoption of Virtual Reality Therapeutics: Randomized Feasibility Pilot Study

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Abstract

Background: Virtual reality therapeutics (VRx) are emerging as a form of digital therapeutics (DTx) with growing evidence for improving symptoms such as anxiety, pain, and distress. However, real-world adoption remains limited because successful use depends not only on the therapeutic benefits but also on how the intervention is introduced, supported, and integrated into care, in addition to the therapeutic benefits. Existing literature has identified barriers related to clinician familiarity, prescribing pathways, onboarding, and independent use outside the clinic, but few studies have experimentally evaluated how implementation strategies influence early adoption outcomes.

Objective: This feasibility pilot study evaluated how different implementation strategies influence early adoption of a VRx intervention in a nonclinical setting by comparing unguided VRx use, self-directed VRx use with implementation materials, and VRx use with prescriber-led consultation and support.

Methods: An institutional review board–approved, 3-arm randomized feasibility pilot study was conducted following the Virtual Reality Clinical Outcomes Research Experts framework and reported using the CONSORT (Consolidated Standards of Reporting Trials) 2010 extension guidelines for pilot and feasibility studies. Participants were randomly allocated to 1 of 3 experimental conditions. Outcomes included technology acceptance, usability, fidelity, and tolerability. Quantitative measures were complemented by qualitative exit interviews. Analyses were exploratory, and the study was not powered for hypothesis testing.

Results: Across conditions, brief VRx exposure was associated with significant improvements in overall technology acceptance ($P<.001$), though postintervention scores remained in the neutral range, indicating early shifts rather than strong endorsement. Participants receiving provider-supported implementation demonstrated the most consistent pattern of favorable outcomes, including higher fidelity of use and significantly greater time-based adherence ($P=.04$). Usability scores were generally favorable across conditions. Tolerability was acceptable, with low levels of reported cybersickness and no discontinuations due to adverse effects. Qualitative findings highlighted the importance of guidance, expectation-setting, and perceived clinical legitimacy in shaping engagement.

Conclusions: This study demonstrates that implementation strategy is a key determinant of adoption for virtual reality–based DTx. By experimentally isolating onboarding and provider support components, this work extends prior efficacy-focused research to address implementation design. Findings suggest that brief provider involvement and structured onboarding may enhance engagement and adherence, supporting future evaluation of scalable DTx implementation models in clinical and community settings.

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KEYWORDS

virtual reality; digital therapeutics; human factors; usability; implementation science

Introduction

Background and Rationale

Anxiety, depression, and chronic pain are among the most prevalent and disabling health conditions globally, affecting hundreds of millions of people and contributing significantly to personal, economic, and societal burden [1-5]. Digital therapeutics (DTx), particularly virtual reality (VR)–based interventions (virtual reality therapeutics [VRx]), are emerging as clinically validated, nonpharmacological treatment options for a range of behavioral and neurological conditions [6-14]. Evidence indicates that VRx can reduce symptoms of anxiety, depression, and pain across diverse populations, including patients with cancer, older adults with chronic disease, and individuals with pain syndromes, in some cases, approaching the effectiveness of standard care [9-12,14-22]. By leveraging mechanisms such as cognitive distraction, immersive meditation, and behavioral engagement, VRx offers a scalable, patient-centered approach to symptom management that may improve access, adherence, and patient experience [9,14,23-29].

Despite promising evidence and reported acceptability, widespread adoption of DTx and VRx remains limited [21,30-35]. Barriers include insufficient provider training, unclear prescribing pathways, cost concerns, and inadequate support for patient onboarding and sustained use [12,25,27,28,36-38]. Additional challenges include workflow integration, technology limitations, and lack of structured implementation strategies [10,17,21,27,33,35,39,40]. While user-related factors such as engagement and personalization have shown positive influence on the adoption of digital interventions [32,39,41], provider behavior, organizational context, and implementation strategy are increasingly recognized as critical but underdeveloped drivers [28,34,42-44].

Many existing VRx studies do not incorporate implementation frameworks or assess perceptual and behavioral outcomes, focusing primarily on symptom efficacy [37,44-50]. As a result, there is limited insight into how patients and providers interact with VRx in real-world contexts, particularly during independent at-home use [7,11,51-54]. While prior studies suggest that patients can use VRx at home with initial training and remote support, most evidence is derived from structured or guided programs, leaving gaps in understanding unsupervised use, adherence, and integration into routine care [11,43,51,54-57]. Addressing these gaps requires experimental evaluation of implementation strategies that more closely reflect real-world use, particularly with respect to provider involvement and support structures.

Research in related areas underscores the importance of implementation structure for digital interventions. Factors such as guidance, integration into daily life, and social connectedness are key influences on engagement with digital health interventions [39], while provider training, resource allocation, and reimbursement remain barriers to VR adoption in clinical settings [58]. Organizational buy-in and workflow integration are also critical for facilitating successful implementation [59]. However, these studies provide limited insight into provider involvement or delivery models for at-home VRx use. Collectively, while evidence supporting digital and VR-based therapeutic interventions is growing, practical strategies for enabling scalable, real-world adoption remain insufficiently defined.

Implementation science provides a useful framework to address these challenges. The Behavior and Acceptance Framework (BEAR) supports systematic identification of barriers and facilitators influencing digital health implementation [60]. It integrates behavioral change theory and technology acceptance concepts to evaluate feasibility, acceptability, usability, and fidelity as key constructs for translating efficacy into real-world adoption [60]. Despite rapid growth in efficacy-focused VRx research, there remains limited experimental evidence evaluating how specific implementation strategies such as the BEAR affect real-world adoption.

Despite demonstrated clinical efficacy, many digital health technologies fail to scale due to barriers in implementation rather than therapeutic limitations. A key gap remains in understanding how provider engagement and structured implementation strategies impact DTx adoption. This study addresses this gap by evaluating how different implementation approaches affect acceptability, usability, and fidelity of VRx among healthy individuals in nonclinical settings. Participants were randomly allocated to one of three conditions: (1) unguided self-use, (2) self-directed use with asynchronous support materials, and (3) provider-supported onboarding with simulated prescription and guided setup. Acceptability and usability were assessed using the technology acceptance model (TAM) [61-63] and System Usability Scale (SUS) [64], and qualitative findings from exit interviews were mapped to BEAR [60] domains to identify implementation-related barriers and facilitators.

By systematically comparing these conditions, this study is, to our knowledge, one of the first to experimentally evaluate the impact of provider-led support versus self-directed implementation strategies on VRx adoption. These findings provide early evidence to inform scalable models for integrating DTx into routine care, particularly by clarifying the role of clinician involvement and structured support in enabling real-world use.

Objectives

The objective of this feasibility pilot study was to evaluate how different implementation strategies influence early adoption of a VRx intervention in a nonclinical setting. Specifically, the study compared unguided VRx use, self-directed VRx use with implementation materials, and provider-supported VRx use with implementation materials to assess differences in acceptability, usability, fidelity, and tolerability. We

hypothesized that participants receiving clinician-supported implementation would demonstrate more favorable adoption-related outcomes than those receiving self-directed support alone or no additional support.

Methods

Study Design

This was a 3-arm pilot study evaluating the acceptability, usability, and fidelity of a VR-based intervention (VRx) and accompanying implementation package across 3 experimental conditions. The study design was guided by the Virtual Reality Clinical Outcomes Research Experts framework [65], and the implementation package design was informed by the BEAR [60] and formative qualitative research with clinicians and end users. This study is reported in accordance with the CONSORT (Consolidated Standards of Reporting Trials) 2010 extension for pilot and feasibility studies [66]. The completed checklist is provided in Checklist 1. The CONSORT-eHEALTH (Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth) checklist [67] was also completed and is provided in Checklist 2.

Participants were allocated to 1 of 3 experimental conditions. As a pilot study, a formal power calculation for hypothesis testing was not performed. Consistent with guidance for feasibility research, approximately 10 - 15 participants per study arm (total N=30 - 45) were targeted for enrollment, which was considered sufficient to assess study procedures, characterize variability in key outcomes, and explore patterns across implementation conditions, while remaining appropriate for an early-stage study [68,69]. Accordingly, the study was not powered to detect statistically significant differences between groups, and findings should be interpreted as exploratory.

A mixed methods approach was used to provide a comprehensive assessment of how implementation strategies and provider engagement influence early adoption. Quantitative measures, such as task completion rates and structured questionnaires, assessed acceptability, usability, and fidelity, and enabled comparison across groups. Qualitative insights from exit interviews contextualized findings by capturing user perspectives, identifying usability challenges, and highlighting perceived benefits and areas for improvement.

Participants

Overview

Study participants were recruited through university listservs, community announcements, and institutional study recruitment platforms. Recruitment and data collection took place between December 2024 and February 2025. Study data were collected and managed using REDCap (Research Electronic Data Capture; Vanderbilt University), hosted at the University of North Carolina at Chapel Hill [70,71].

Of the 39 participants enrolled, 31 (79.5%) completed the study and were included in the final analysis.

Eligibility Criteria

Participants were eligible for inclusion if they were adults aged 18 - 65 years, were in good general health with no safety concerns for VR use, and had no history of psychiatric or neurological conditions that could be exacerbated by VR exposure (eg, epilepsy or seizure disorders, severe motion sensitivity, vestibular disorders, or conditions associated with sensory overstimulation). Additional inclusion criteria included limited prior VR experience (defined as fewer than 2 lifetime uses), the ability to provide informed consent, and a motion sickness score below 21.6 on the prescreening assessment. Full screening instruments, including VR safety and prior experience questions used for eligibility screening, are provided in Multimedia Appendix 1.

Study Setting

This study was conducted outside of a clinical setting, in either (1) a human factors laboratory designed to simulate a home-like environment or (2) a community-based setting (eg, private library study spaces and private community center spaces). Measures were taken to ensure privacy, confidentiality, and consistent study procedures across all settings.

Adverse Events and Safety Monitoring

Screening procedures were used to minimize the risk of adverse events. Individuals who did not meet the inclusion criteria were not enrolled. No adverse events were reported during the study. Cybersickness susceptibility was assessed during screening using the Motion Sickness Susceptibility Questionnaire—Short Form [72]. Participants with severe susceptibility to motion sickness were excluded. Prior to VRx use and immediately following, participants were screened using the Cybersickness in Virtual Reality Questionnaire (CSQ-VR) [73] to minimize cybersickness risk and assess symptoms. Participants were instructed to discontinue use if symptoms occurred, with study personnel present to ensure safety.

Randomization

Participants were randomly allocated to 1 of 3 experimental conditions with a target 1:1:1 allocation ratio. The allocation sequence was generated in Microsoft Excel using the RAND() function prior to study initiation. Simple randomization was used; no formal blocking or stratification was applied. Assignments were made by study team members at the time of scheduling, with each enrolled participant assigned to the next available condition in the allocation sequence. Because recruitment, scheduling, and data collection occurred in parallel over a defined recruitment window (December 2024-February 2025), target group sizes were monitored during enrollment; when a scheduled participant did not attend their session, a subsequent enrolled participant was assigned to the affected condition to maintain approximate group sizes across arms. Self-reported technology comfort level and prior VR experience were monitored as baseline characteristics but were not used as formal allocation variables.

Allocation concealment from study personnel was not implemented, as schedulers required visibility of assignments to prepare condition-specific materials in advance of each session. Full blinding of participants and study personnel was

not feasible, given the unavoidably visible differences between study arms, for example, the presence of a provider in condition 3 and the presence of physical implementation materials in conditions 2 and 3. To minimize expectancy effects, participants were not informed of their assigned condition until arrival for their study appointment. The absence of allocation concealment and blinding is acknowledged as a limitation.

Intervention

The intervention consisted of art therapy delivered using the application OpenBrush on an Oculus Quest 2 headset. Participants were instructed to complete a series of drawing tasks over a 20-minute session. Further information about OpenBrush and selection of the application is provided in Multimedia Appendix 2.

Condition-specific materials (eg, comfort accessories, tutorials, chatbot, or provider consultation) were provided to participants as outlined in Table 1. Detailed implementation package elements, equipment lists, and task protocols are provided in Multimedia Appendix 3. Differences between experimental conditions across stages of implementation are summarized in Figure 1. Representative screenshots of the VRx application interface are shown in Figure 2.

Table . Overview of experimental conditions and levels of implementation support in a 3-arm randomized feasibility pilot study of virtual reality therapeutics (VRx) conducted among healthy adults in nonclinical settings at the University of North Carolina at Chapel Hill (December 2024-February 2025).

Condition	Description	Intervention details
1. Unguided use	Self-directed use with no onboarding or support materials	Virtual reality headset preloaded with VRx application, minimal instructions
2. Self-directed support	Self-directed use with asynchronous support materials	Headset with VRx application and comfort accessories, quick start guides, tutorial, chatbot support
3. Provider-led support	Implementation package plus a simulated provider encounter	Same as condition 2, plus a 5-minute scripted provider consultation including mock diagnosis, virtual reality fitness check, and guided first use

Figure 1. Conceptual overview of the implementation support solution components used across the VRx adoption journey in a 3-arm feasibility pilot study. All participants moved through the same 6 implementation stages, while support increased from unguided use to self-directed support materials and provider-led onboarding. Detailed condition-specific components are provided in Table 1 and Multimedia Appendix 3. VRx: virtual reality therapeutics.

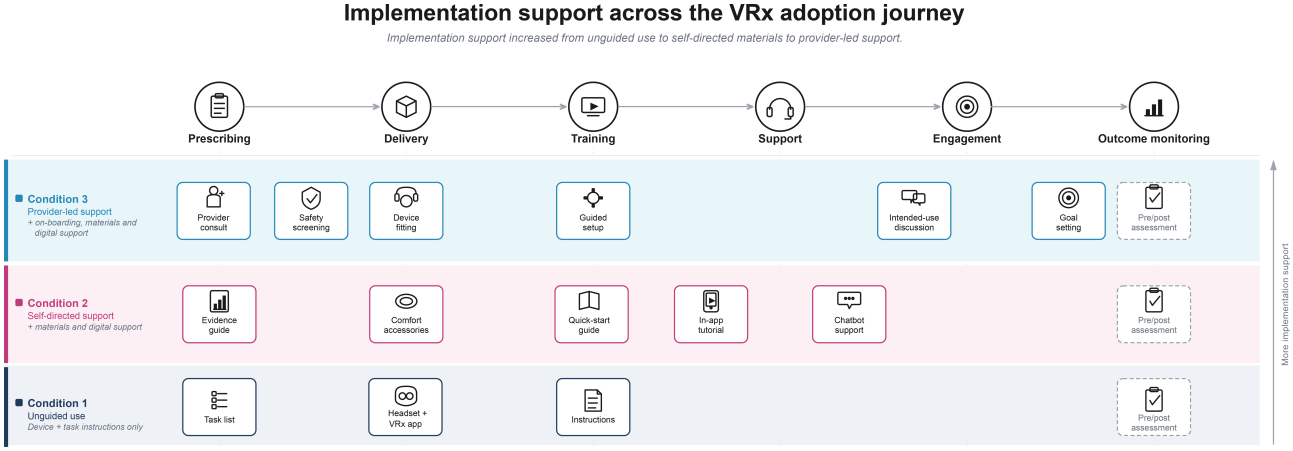
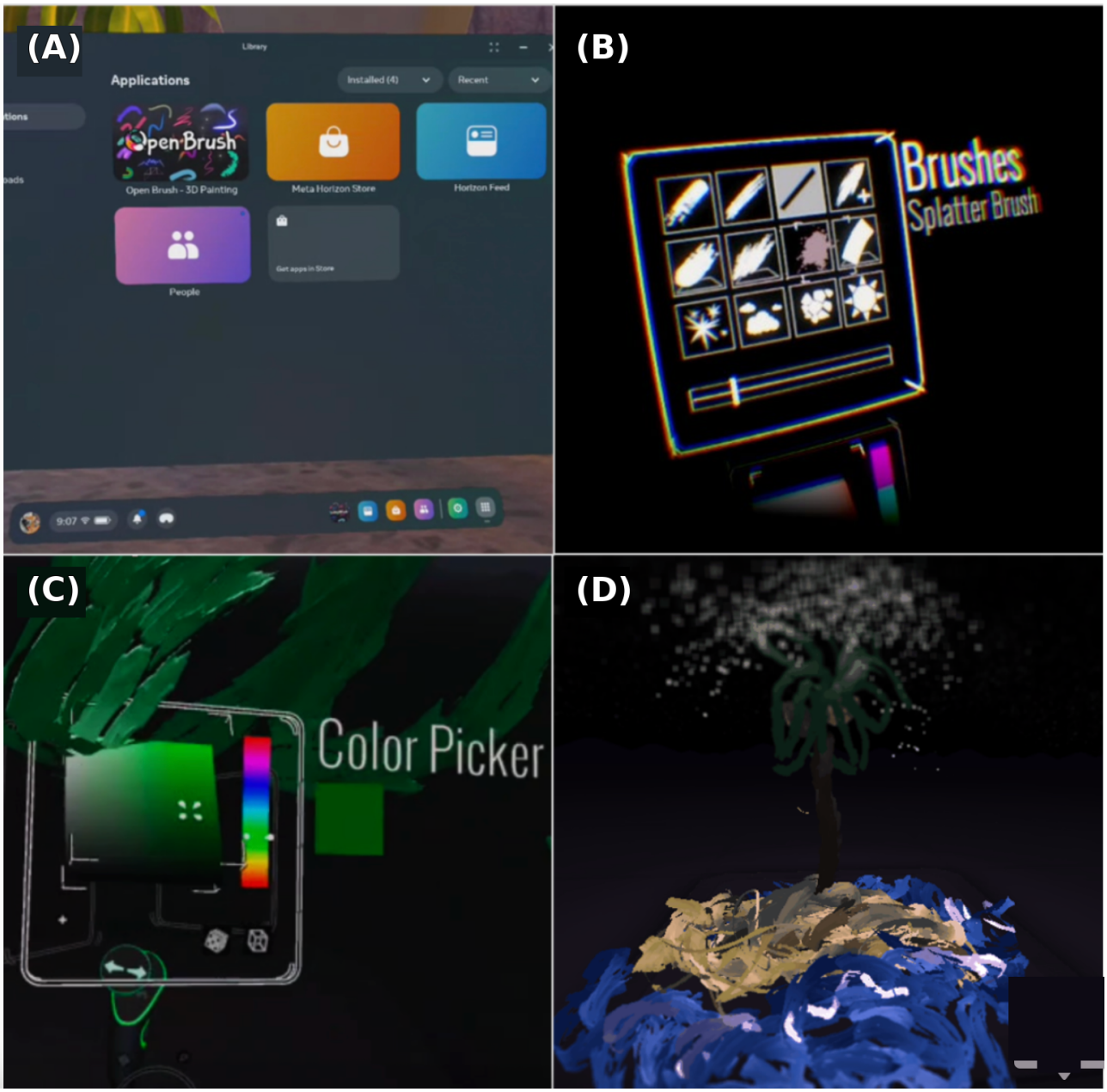


Figure 2. Representative images of the OpenBrush virtual reality application used in the study. (A) OpenBrush application shown in the headset application library. (B) In-app brush selection menu. (C) In-app color picker tool. (D) Example 3D drawing created in OpenBrush.



The implementation package was developed based on prior qualitative research conducted by the study team exploring barriers to VRx adoption and was informed by the BEAR [60] and Virtual Reality Clinical Outcomes Research Experts framework [65] to address key implementation barriers across 6 stages of the implementation process. Package components included comfort accessories to improve device ergonomics, paper-based quick reference guides, a clinical evidence infographic, and an in-app step-by-step tutorial. The VR system menu was preconfigured for conditions 2 and 3 to display only the therapeutic application, reducing navigation complexity. A support chatbot was developed to provide real-time troubleshooting assistance. A complete description of all implementation package components, including photographs, equipment specifications, training documents, and the chatbot development process, is provided in Multimedia Appendix 3.

In the provider-supported condition, participants engaged in a standardized, scripted interaction delivered by a trained research team member with clinical training (eg, medical students). The interaction simulated a brief clinical encounter introducing VRx, including an explanation of the intervention, expected benefits, guidance on use, and a brief safety screening and device fitting. Interactions were time-limited (<5 minutes) and delivered using a predefined script to ensure consistency, as provided in Multimedia Appendix 3.

All individuals delivering the interaction were trained on the script and protocol prior to study initiation, and the script was followed closely to ensure standardized delivery. A checklist-based approach was used to ensure that all key components of the interaction were delivered consistently across participants. The provider consultation script and materials were developed based on prior qualitative research conducted by the

study team exploring clinician perspectives on DTx and VRx and were designed to simulate a realistic clinical interaction.

Data Collection

Participants completed questionnaires at session initiation and immediately following intervention use. All measurement instruments administered in this study, including screening tools and outcome measures, are provided in Multimedia Appendix 4. Observational data, including task performance, errors, help requests, and adherence, were recorded by trained observers using a structured checklist (Multimedia Appendix 5). For conditions 2 and 3, the use of implementation system components and the time spent were also recorded.

Exit interviews were conducted immediately following the session to capture user perceptions, barriers, and facilitators related to intervention use.

Primary outcomes included acceptability, usability, and fidelity; tolerability was assessed as a secondary outcome. Validated measurement instruments and techniques were used to collect both subjective and objective data, which are summarized in Table 2.

Table . Summary of measurement instruments used in a 3-arm pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

Construct	Measurement	Framework	Classification
Acceptability	TAM3[b]-based pre- or postquestionnaires, time in virtual reality, behavioral observations	TAM [61-63]	Subjective+objective
Usability	Task completion, error rates, help requests, time to complete, SUS[c] scores	SUS [64], task analysis	Objective+subjective
Fidelity	Adherence to protocol, task completion, duration, motivation (time engaged)	Adherence metrics	Objective
Tolerability	Pre- or postcybersickness questionnaire	CSQ-VR[d] [73]	Subjective
Qualitative insights	Exit interviews	BEAR[e] [60]	Subjective

[a]Measures collected subjective and objective data at 3 time points: during screening, at session initiation, and immediately following intervention use.

[b]TAM: technology acceptance model.

[c]SUS: System Usability Scale.

[d]CSQ-VR: Cybersickness in Virtual Reality Questionnaire.

[e]BEAR: Behavior and Acceptance Framework.

Data Analysis

Acceptability

Acceptability was assessed using a TAM-based questionnaire administered before and after the intervention, capturing perceived usefulness (PU), perceived ease of use (PEU), attitude toward technology (ATT), and behavioral intention to use (BI). Questions used a 5-point Likert scale for response.

Objective indicators of acceptability included time spent in VR and behavioral engagement during the session.

Usability

Usability was evaluated using both objective and subjective measures, including task completion rates, error frequency, help requests, time to complete tasks, and SUS scores [64,74,75].

A modified SUS was used, with 2 items removed due to the limited complexity of the system. Scores were rescaled to a 0 - 100 range. Given this modification, results are interpreted descriptively and are not directly comparable to standard SUS benchmarks.

Fidelity

Fidelity was assessed through adherence to the study protocol, including task completion, duration of engagement, and time-based adherence. Observational measures captured whether participants followed intended workflows versus engaging in exploratory behaviors.

Tolerability

Tolerability was assessed using the CSQ-VR [73], administered before and after the intervention. This measure assessed participant perceptions of discomfort and was used to monitor for potential adverse events and evaluate the role of preintervention screening in supporting safe VRx use.

Qualitative Insights

Exit interviews were conducted using a structured guide informed by the BEAR [60] to capture participant perceptions, barriers, and facilitators to VRx use. Following the approach of Braun and Clarke [76] to reflective thematic analysis, responses were evaluated using an iterative, inductive process including familiarization with the data through repeated reading of the interview notes, generation of initial codes, and grouping of codes into themes. Themes were then iteratively reviewed, refined, and defined to capture patterned meaning across

participant experiences. Resulting themes were mapped to constructs from the BEAR to contextualize findings relative to implementation-relevant barriers and facilitators.

Statistical Analysis

Overview

Data normality was assessed using Shapiro-Wilk tests. As several variables violated normality assumptions, nonparametric statistical tests were used.

Consistent with pilot study recommendations, analyses were structured to characterize the direction and magnitude of effects rather than to test formal hypotheses. Analyses were categorized as primary, secondary, or exploratory. All statistical analyses were conducted using R software (R Foundation for Statistical Computing).

Primary Analysis

Pre- and postchanges in overall TAM scores were assessed using Wilcoxon signed rank tests. Effect sizes were calculated as $r=Z/\sqrt{N}$, with 95% CIs estimated using bias-corrected and accelerated bootstrapping (2000 resamples).

Observational and behavioral data (eg, task performance, adherence, and engagement time) were summarized using descriptive statistics.

Secondary Analysis

Between-group differences in acceptability, usability, and fidelity outcomes were evaluated using Kruskal-Wallis tests. Where significant, post-hoc pairwise comparisons were conducted using Wilcoxon rank sum tests with Bonferroni-adjusted *P* values. TAM construct-level pre- and postchanges (PU, PEU, ATT, and BI) were assessed across the full sample using Wilcoxon signed rank tests. Overall TAM pre- and postchange was additionally examined within each experimental condition. Effect sizes were calculated as $r=Z/\sqrt{N}$, with 95% CIs estimated using bias-corrected and accelerated bootstrapping (2000 resamples).

Exploratory Analysis

Construct-level TAM analyses by experimental condition and SUS item-level analyses were conducted on an exploratory basis. SUS item-level analyses were conducted descriptively to characterize usability patterns across conditions. No corrections for multiple comparisons were applied to exploratory analyses, and findings should be interpreted based on overall patterns rather than individual construct-level comparisons. Additional exploratory subgroup analyses examined associations between participant characteristics and outcomes.

Modified SUS

A modified SUS [64] was used, with 2 items removed due to limited system complexity: “I found the various functions in this system were well integrated” and “I thought there was too much inconsistency in this system.” Scores were rescaled to a 0 - 100 range. Analyses were conducted at the total score level; item-level responses were interpreted descriptively. This modification may limit direct comparability to standard SUS scores and benchmarks and is acknowledged as a limitation of the study.

Multiple Comparisons

Bonferroni corrections were applied to post-hoc pairwise comparisons. No corrections were applied to within-group or exploratory analyses, consistent with the hypothesis-generating nature of pilot studies [77].

Exploratory subgroup analyses examining associations between participant demographic characteristics (eg, age, education level, technology comfort, prior VR experience) and primary outcomes were conducted to assess for potential confounding; these analyses are reported in Multimedia Appendix 6. The associated risk of inflated type I error for uncorrected comparisons is acknowledged in the Limitations section.

Ethical Considerations

This study was reviewed and approved by the UNC Institutional Review Board (IRB) at The University of North Carolina at Chapel Hill (IRB: 24 - 2894). The study was determined to meet criteria for approval under federal regulations governing human subjects research, and all procedures were conducted in accordance with applicable ethical guidelines. All participants provided informed consent prior to enrollment. The consent process included a detailed explanation of the study purpose, procedures, risks, and the voluntary nature of participation. The informed consent form is provided in Multimedia Appendix 1. To protect participant privacy and confidentiality, all data collected were deidentified and stored securely using REDCap [70,71]. Personally identifiable information was removed from all research records, and data were stored without participant names. No identifying information is disclosed in any publications resulting from this research. Figures depicting the VR intervention (Figure 2) show application screenshots only, and no photographs of participants were included in the multimedia appendices. Participants did not receive financial compensation for their participation in this study. This study was not prospectively registered, as it was designed as a pilot feasibility study focused on evaluating implementation strategies and process outcomes (eg, acceptability, usability, and fidelity) rather than clinical efficacy or health outcomes. This approach is consistent with guidance indicating that formative and feasibility studies examining implementation processes and user perceptions do not require trial registration. All study procedures and outcome measures were predefined in the IRB-approved protocol prior to data collection, and no outcomes were modified after enrollment began.

Results

Participant Characteristics

Of the 39 participants enrolled, 31 (79.5%) completed the study and were included in the final analysis. In total, 8 participants did not complete the study due to logistical factors (n=6) or study-related factors (n=2), specifically the lack of monetary incentive.

Participants had a mean age of 38.6 (SD 12.3; range 18 - 64) years, and the sample was predominantly female (20/31, 64.5%).

Figure 3 presents a CONSORT-style participant flow diagram, and Table 3 summarizes the demographic characteristics by experimental condition.

Figure 3. CONSORT flow diagram [78] illustrating participant progress through enrollment, intervention allocation, follow-up, and data analysis in a 3-arm pilot study of virtual reality therapeutics conducted from December 2024 to February 2025. CONSORT: Consolidated Standards of Reporting Trials.

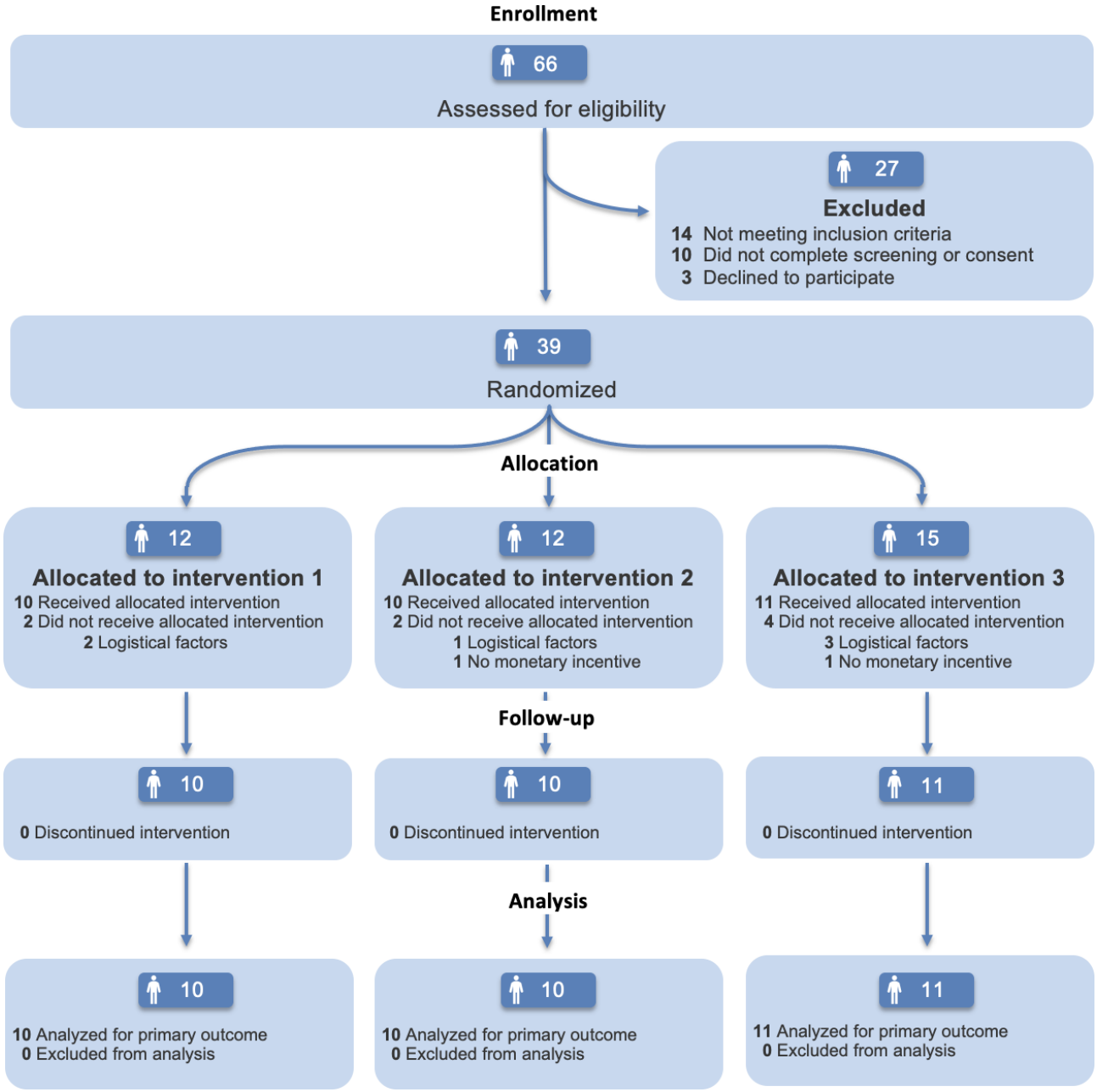


Table . Demographic characteristics of study participants in a 3-arm pilot study of virtual reality (VR) therapeutics conducted from December 2024 to February 2025.

Characteristic	Overall (N=31)	Condition 1 (n=10)	Condition 2 (n=10)	Condition 3 (n=11)
Age (years), mean (SD)	38.6 (12.3)	37.3 (12.6)	40.9 (12.6)	37.6 (12.6)
Sex, n (%)				
Female	20 (64.5)	4 (40)	7 (70)	9 (81.8)
Male	10 (32.3)	6 (60)	3 (30)	1 (9.1)
Other	1 (3.2)	0 (0)	0 (0)	1 (9.1)
Education, n (%)				
High school diploma or GED	2 (6.5)	1 (10)	1 (10)	0 (0)
Some college, no degree	3 (9.68)	2 (20)	0 (0)	1 (9.1)
Associate degree	1 (3.3)	0 (0)	0 (0)	1 (9.1)
Bachelor degree	7 (22.6)	2 (20)	3 (30)	2 (18.1)
Master degree	13 (41.9)	3 (30)	4 (40)	6 (54.5)
Doctoral or professional degree	5 (16.1)	2 (20)	2 (20)	1 (9.1)
Employment, n (%)				
Employed full-time	17 (54.8)	6 (60)	5 (50)	6 (54.5)
Employed part-time	4 (12.9)	1 (10)	2 (20)	1 (9.1)
Self-employed	3 (9.7)	1 (10)	2 (20)	0 (0)
Student	5 (16.1)	2 (20)	1 (10)	2 (18.2)
Unemployed, looking for work	1 (3.2)	0 (0)	0 (0)	1 (9.1)
Unemployed, not looking for work	1 (3.2)	0 (0)	0 (0)	1 (9.1)
Overall technology comfort level, n (%)				
Low	16 (51.6)	4 (40)	6 (60)	6 (54.5)
Medium	15 (48.4)	6 (60)	4 (40)	5 (45.5)
Prior VR experience, n (%)				
Somewhat familiar	15 (48.4)	6 (60)	3 (30)	6 (54.5)
Never used	14 (45.2)	4 (40)	5 (50)	5 (45.5)
N/A—never heard of	2 (6.45)	0 (0)	2 (20)	0 (0)

Participant characteristics, including self-reported technology comfort and prior VR experience, were monitored during enrollment to assess balance across conditions. Participants were categorized as having low (16/31, 51.6%) or medium (15/31, 48.4%) technology comfort levels. Participants were assigned to experimental conditions according to a prespecified allocation sequence, with condition assignments made at the time of scheduling. Group comparisons indicated no significant differences in baseline demographic characteristics, including age, education level, or employment status.

Exploratory subgroup analyses examining associations between participant demographic characteristics and primary outcomes are reported in Multimedia Appendix 6. With the exception of acceptability scores, which differed significantly across age groups (χ^2_4=10.1; P=.04; ηH^2=0.235), no significant associations were identified. Given the small subgroup sizes and exploratory nature of this analysis, the age-related acceptability finding should not be interpreted as evidence of confounding and warrants further investigation in future adequately powered studies.

Acceptability Outcomes

Overall TAM Results

Overall, technology acceptance demonstrated statistically significant increases following intervention exposure across the full sample (Figure 4). Mean TAM scores increased from 2.84 (SD 0.32) before the intervention to 3.22 (SD 0.45) after the intervention, representing a statistically significant improvement

with a large effect size (P<.001; r=0.75, 95% CI 0.64-0.82; Table 4). However, absolute postintervention scores remained near the midpoint of the scale, indicating overall neutral to moderate levels of acceptance rather than high acceptance.

Figure 4. Pre- and postintervention TAM scores by experimental condition in a 3-arm randomized feasibility pilot study of VRx conducted from December 2024 to February 2025. Mean TAM scores increased across all conditions following intervention exposure; however, postintervention scores remained near the midpoint of the scale, indicating moderate rather than high levels of acceptance. TAM: technology acceptance model; VRx: virtual reality therapeutics.

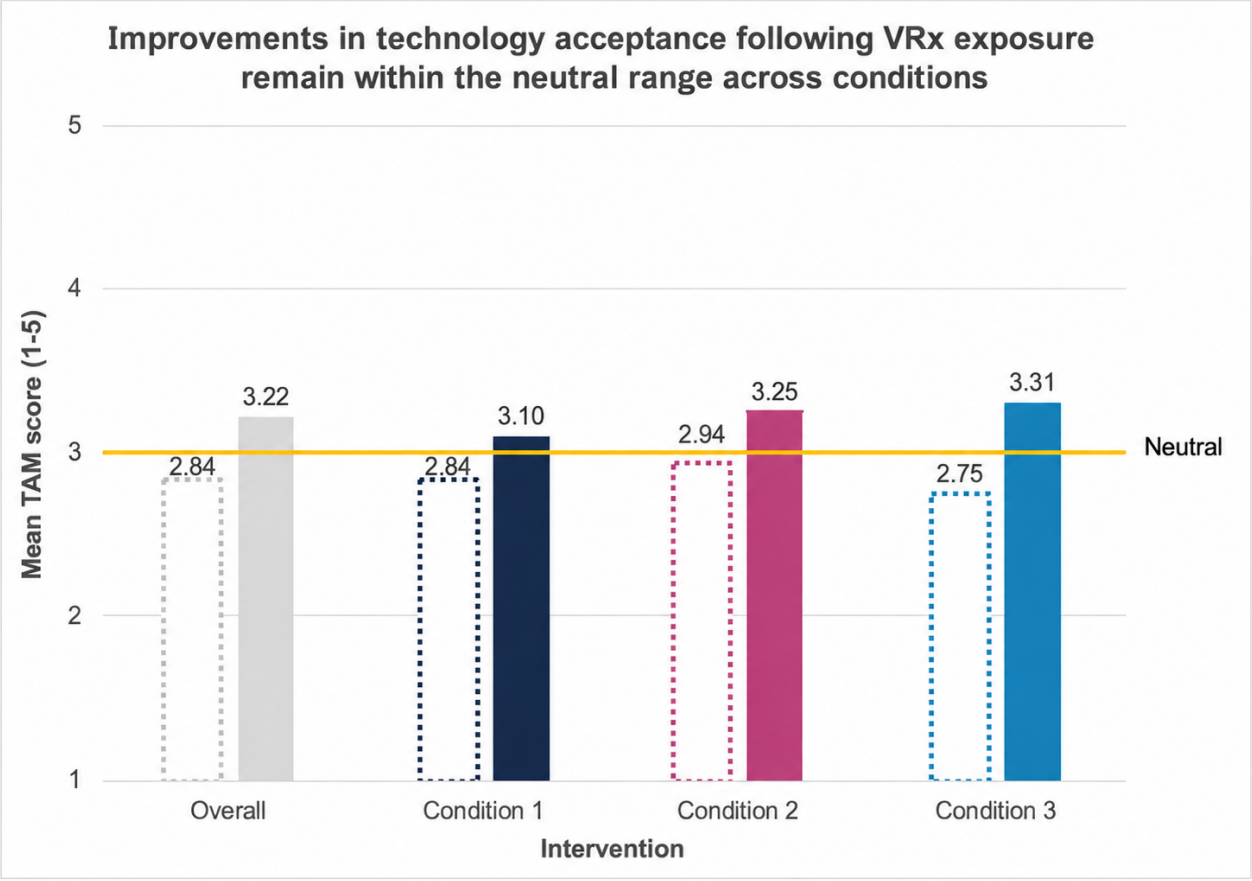


Table . Pre- and postchanges in overall mean technology acceptance model scores by experimental condition (N=31) in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

Condition	Values, n	Preintervention, mean (SD)	Postintervention, mean (SD)	Δ Mean	*W*	*P* value[b] (Wilcoxon)	Effect size, *r* (95% CI)
Condition 1 unguided use	10	2.84 (0.40)	3.10 (0.53)	+0.26	0	.03	0.70 (0.42-0.80)
Condition 2 self-directed support	10	2.94 (0.27)	3.25 (0.49)	+0.31	4	.03	0.70 (0.14-0.85)
Condition 3 provider-led support	11	2.75 (0.29)	3.31 (0.34)	+0.56	0	.005	0.85 (0.66-0.89)
Overall sample	31	2.84 (0.32)	3.22 (0.45)	+0.38	7	<.001	0.75 (0.64-0.82)

[a]Technology acceptance model scores are based on a Likert scale from 1 to 5. Pre- and postdifferences were assessed using Wilcoxon signed rank tests. Effect sizes are reported as $r=Z/\sqrt{N}$. 95% CIs were estimated using bias-corrected and accelerated bootstrapping (2000 resamples). Δ Mean represents the difference between preintervention and postintervention scores. This table reflects primary (overall sample) and secondary (condition-level) analyses.

[b]*P* values are reported for all comparisons; statistical significance was defined as P<.05.

At the intervention condition level, statistically significant improvements were observed across all 3 experimental conditions (Table 4). The largest improvement was observed in condition 3 (provider-led support), followed by condition 2 (self-directed support) and condition 1 (unguided use). These findings suggest that more structured implementation approaches were associated with greater improvements in technology acceptance. Despite these improvements, absolute TAM scores across all conditions remained near the midpoint of the 5-point scale, indicating that while acceptability shifted from slightly

below neutral to slightly above neutral, none of the conditions achieved a high level of acceptance.

TAM construct-level changes are summarized in Table 5; constructs examined included PU, PEU, ATT, and BI [61-63]. Across the full sample, all constructs demonstrated statistically significant improvements following intervention exposure. Effect sizes were large for PU, ATT, and BI (r=0.64, 0.63, and 0.67, respectively) and medium for PEU (r=0.48). Mean PU increased by 0.40 from 2.87 (SD 0.41) to 3.27 (SD 0.53), mean PEU increased by 0.30 from 2.89 (SD 0.53) to 3.19 (SD 0.56), mean ATT increased by 0.37 from 3.02 (SD 0.46) to 3.39 (SD 0.50), and mean BI increased by 0.45 from 2.58 (SD 0.41) to 3.03 (SD 0.64). The largest absolute improvement was observed in BI, followed by PU and ATT, while PEU demonstrated a more modest increase in comparison.

Table . Pre- and postchanges in overall mean technology acceptance model (TAM) scores at the construct level in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

TAM construct	Preintervention, mean (SD)	Postintervention, mean (SD)	Δ Mean	*W*	*P* value[b] (Wilcoxon)	Effect size, *r* (95% CI)
Perceived usefulness	2.87 (0.41)	3.27 (0.53)	+0.40	0	<.001	0.64 (0.51-0.74)
Perceived ease of use	2.89 (0.53)	3.19 (0.56)	+0.30	35	.007	0.48 (0.14-0.68)
Attitude toward technology	3.02 (0.46)	3.39 (0.50)	+0.37	0	.001	0.63 (0.49-0.72)
Behavioral intention to use	2.58 (0.41)	3.03 (0.64)	+0.45	16	<.001	0.67 (0.43-0.78)
Overall TAM	2.84 (0.32)	3.22 (0.45)	+0.38	7	<.001	0.75 (0.64-0.82)

[a]Values represent the mean pre- and postintervention TAM scores and corresponding mean change (Δ mean) within each TAM construct. TAM scores are based on a Likert scale (range 1-5). Pre- and postdifferences were assessed using Wilcoxon signed rank tests. Effect sizes are reported as $r=Z/\sqrt{N}$. 95% CIs were estimated using bias-corrected and accelerated bootstrapping with 2000 resamples. Δ Mean represents the difference between preintervention and postintervention scores. This table reflects TAM construct-level analyses conducted across the overall sample (N=31).

[b]*P* values are reported for all comparisons; statistical significance was defined as $P<.05$.

Despite these statistically significant improvements across all constructs, postintervention scores remained near the midpoint of the scale (~3.0 - 3.4), indicating moderate rather than high levels of acceptance. While improvements reflect a greater openness to VRx, postintervention results for intention to use remained comparatively lower than other constructs, suggesting that increased acceptance did not fully translate into strong intention to adopt.

Exploratory Between-Condition Construct-Level Results

Exploratory construct-level changes by experimental condition are presented descriptively in Table 6, with full inferential statistical results reported in Multimedia Appendix 6.

Table . Exploratory construct-level changes in mean technology acceptance model (TAM) scores by experimental condition in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

TAM construct	Condition 1			Condition 2			Condition 3		
	Preintervention, mean (SD)	Postintervention, mean (SD)	Δ Mean	Preintervention, mean (SD)	Postintervention, mean (SD)	Δ Mean	Preintervention, mean (SD)	Postintervention, mean (SD)	Δ Mean
Perceived usefulness	2.80 (0.42)	3.20 (0.63)	+0.40	3.10 (0.21)	3.30 (0.48)	+0.20	2.73 (0.47)	3.32 (0.51)	+0.59
Perceived ease of use	3.00 (0.33)	3.00 (0.47)	+0.00	2.70 (0.63)	3.05 (0.60)	+0.35	2.95 (0.57)	3.50 (0.50)	+0.55
Attitude toward technology	3.10 (0.61)	3.35 (0.53)	+0.25	3.15 (0.34)	3.45 (0.50)	+0.30	2.82 (0.34)	3.36 (0.50)	+0.54
Behavioral intention to use	2.45 (0.55)	2.85 (0.78)	+0.40	2.80 (0.35)	3.20 (0.63)	+0.40	2.50 (0.22)	3.05 (0.52)	+0.55
Overall TAM	2.84 (0.40)	3.10 (0.53)	+0.26	2.94 (0.27)	3.25 (0.49)	+0.31	2.75 (0.29)	3.31 (0.34)	+0.56

[a]Values represent mean pre- and postintervention TAM construct-level scores and corresponding mean change (Δ mean) within each condition. TAM scores are based on a Likert scale from 1 to 5. These analyses are exploratory and descriptive; inferential statistical results including *P* values and effect sizes are reported in Multimedia Appendix 6. No correction for multiple comparisons was applied to exploratory analyses; results should be interpreted in the context of the overall patterns.

In condition 1 (unguided use), improvements were observed primarily in BI and overall TAM scores, with smaller or negligible changes across PU, PEU, and ATT. Condition 2 (self-directed support) demonstrated modest and relatively consistent improvements across all constructs; however, the magnitude of change was generally limited and did not show clear differentiation across constructs.

In contrast, condition 3 (provider-led support) exhibited the largest and most consistent improvements across all TAM constructs. These findings suggest that more structured, human-directed implementation approaches may be associated with broader and more meaningful gains in technology acceptance, particularly in translating improvements across multiple acceptance domains.

As these analyses were exploratory and no correction for multiple comparisons was applied, findings should be interpreted in the context of overall patterns rather than individual construct-level differences.

Engagement and Satisfaction Results

Participants spent an average of 17.00 (SD 5.45) minutes engaging with the VRx intervention. Descriptive engagement and acceptability metrics by experimental condition are summarized in Table 7.

Table . Engagement and acceptability metrics in the overall sample and by experimental condition in a 3-arm feasibility pilot study of virtual reality therapeutics (VRx) conducted from December 2024 to February 2025.

Experimental condition	Values, n	Mean duration in VRx (SD) (minutes)	Mean task completion rate (SD) (%)	Mean virtual reality engagement (SD) (%)	Mean acceptability score (SD)	Mean acceptability (SD) (%)
Condition 1 unguided use	10	13.80 (6.66)	94.6 (4.5)	56.7 (41.7)	150.0 (28.3)	88.2 (16.6)
Condition 2 self-directed support	10	17.10 (4.82)	93.7 (4.7)	73.3 (34.4)	138.0 (32.4)	81.2 (19.1)
Condition 3 provider-led support	11	19.82 (3.03)	95.8 (3.7)	93.9 (13.5)	149.6 (16.7)	88 (9.8)
Overall sample	31	17.00 (5.45)	94.7 (4.3)	75.3 (34.4)	146.0 (26.1)	85.9 (15.3)

Engagement time varied by condition, with participants in condition 3 (provider-led support) demonstrating the longest duration in VRx (mean 19.82, SD 3.03), followed by condition 2 (self-directed support; mean 17.10, SD 4.82) and condition 1 (unguided use; mean 13.80, SD 6.66). A similar directional pattern was observed across VR engagement and acceptability measures, with condition 3 showing the highest levels overall.

A statistically significant difference across conditions was observed for time spent in VRx (Kruskal-Wallis χ^2_2=6.7; *P*=.04; ηH^2=0.222). Exploratory post-hoc pairwise comparisons with

Bonferroni correction suggested that participants in condition 3 spent significantly more time in VRx compared to those in condition 1 (adjusted *P*=.046) with no statistically significant differences observed between other condition pairs (Table 8). No statistically significant between-group differences were observed for task completion rate, VR engagement percentage, or acceptability scores.

Table . Post-hoc Wilcoxon pairwise analysis with Bonferroni correction findings suggest that participants in condition 3 spent significantly more time in virtual reality therapeutics (VRx) compared to those in condition 1[a].

Experimental condition	N1	N2	Wilcoxon statistics	*P* value	*P*.adj
Condition 1 versus condition 2	10	10	34.5	.25	.76
Condition 1 versus condition 3[b]	10	11	20.5	.02	.046
Condition 2 versus condition 3	10	11	33.5	.13	.39

[a]Analysis is comparing time in VRx within experimental conditions in a 3-arm randomized feasibility pilot study of VRx conducted from December 2024 to February 2025.

[b]Significant difference (*P*<.05).

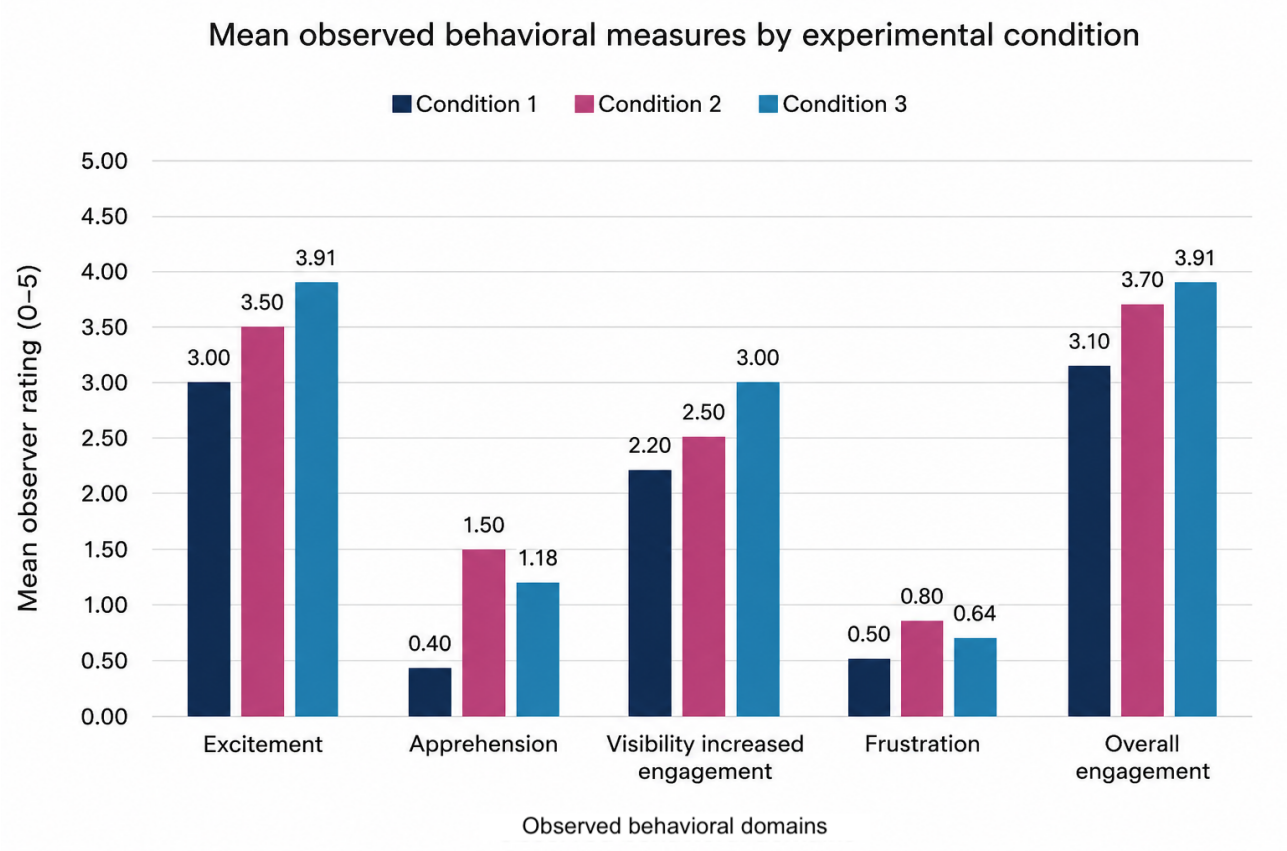
These findings suggest that more structured implementation approaches may support deeper engagement with VR interventions, although this effect was primarily reflected in time spent in VRx rather than broader engagement or acceptability measures. Given the exploratory nature of these analyses, the limited sample size, and the reliance on a single pairwise comparison, this finding should be interpreted with caution.

Self-efficacy and satisfaction followed a similar descriptive pattern, with participants in condition 3 reporting the highest scores (self-efficacy: mean 2.97, SD 0.46; satisfaction: mean 3.59, SD 0.44). Across all conditions, mean self-efficacy was 2.88 (SD 0.46), and mean satisfaction was 3.50 (SD 0.45). These measures were not formally compared across conditions and should be interpreted descriptively.

Observed Behavioral Results

Observed behavioral measures varied across experimental conditions (Figure 5). Participants in condition 3 (provider-led support) demonstrated higher levels of excitement and overall engagement, along with lower levels of frustration relative to other conditions. In contrast, participants in condition 2 (self-directed support) exhibited relatively higher levels of apprehension and frustration despite receiving supplemental implementation materials. Participants in condition 1 (unguided use) showed lower excitement and overall engagement in comparison to the other conditions.

Figure 5. Observed behavioral measures across experimental conditions. Mean observer ratings for excitement, apprehension, visible increased engagement, frustration, and overall engagement are shown for each condition. Higher engagement and excitement, along with lower frustration, were observed among participants receiving provider-led support (condition 3).



These observational patterns suggest that provider-led implementation support may be associated with more positive behavioral responses during VR use, including increased engagement and reduced frustration. Notably, self-directed support materials (condition 2) did not appear to reduce apprehension or frustration, suggesting that the presence of materials alone may be insufficient without structured guidance. As these measures were observational and not statistically tested, findings should be interpreted as descriptive.

Usability Outcomes

Objective Task Performance Metrics Results

Usability metrics by condition are summarized in Table 9. Overall task completion rates were high (mean 94.7%, SD 4.3%), with similar performance across conditions. The lowest mean number of errors was observed in condition 3 (provider-led support; mean 2.09, SD 1.76), while condition 2 (self-directed support) had the fewest help requests (mean 1.60, SD 2.12). Mean usability scores were highest in condition 3 (mean 61.64, SD 12.86; mean 77.4%, SD 16.1%), followed by condition 2 (mean 58.90, SD 8.26; mean 73.8%, SD 10.3%) and condition 1 (mean 56.50, SD 13.55; mean 70.8%, SD 16.9%).

Table . Usability measures (task completion rate, errors, help requests, and scores) by experimental condition in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025.

Experimental condition	Mean task completion rate (SD) (%)	Mean number of errors (SD)	Mean help requests (SD)	Mean observed usability score (SD)	Mean usability score (SD) (%)
Condition 1 (n=10)	94.6 (4.5)	3.30 (2.11)	2.22 (1.39)	56.50 (13.55)	70.8 (16.9)
Condition 2 (n=10)	93.7 (4.7)	3.50 (1.96)	1.60 (2.12)	58.90 (8.26)	73.8 (10.3)
Condition 3 (n=11)	95.8 (3.7)	2.09 (1.38)	2.09 (1.76)	61.64 (12.86)	77.4 (16.1)
Overall (N=31)	94.7 (4.3)	2.94 (1.88)	1.97 (1.75)	59.10 (11.63)	74.1 (14.5)

Help requests were examined to characterize usability challenges across conditions. The most common requests were related to navigating the VR system, selecting menu options, and exiting the application. Task 1 generated the highest number of help requests, particularly for powering on the device, setting up boundaries, and using the controllers. These findings suggest that initial onboarding and system navigation represent key usability challenges in VR-based interventions.

SUS Results

Overall SUS scores summarized in Table 10 indicated relatively high usability scores across the full sample (mean 83.74, SD 12.52), with condition 3 demonstrating the highest mean score (mean 88.26, SD 10.34), followed by condition 2 (mean 82.50, SD 14.00) and condition 1 (mean 80.00, SD 12.85). No statistically significant between-group differences were observed (Kruskal-Wallis χ^2_2=2.3; *P*=.31). Given the modified scale used in this study, scores are interpreted as a relative measure of usability across conditions rather than against standard SUS benchmarks.

Table . System Usability Scale (SUS) scores by experimental condition in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

Experimental condition	Values, n	Mean SUS score (SD)
Condition 1	10	80.00 (12.85)
Condition 2	10	82.50 (14.00)
Condition 3	11	88.26 (10.34)
Overall	31	83.74 (12.52)

[a]Between-group differences were assessed using Kruskal-Wallis tests. No statistically significant between-group differences were observed for SUS scores (χ^2_2=2.3; *P*=.31).

Exploratory item-level findings are presented in Multimedia Appendix 6 and interpreted descriptively. Across conditions, higher ratings were observed for intention to use and PEU, while lower ratings were observed for learnability and need for assistance, suggesting that onboarding and independent use represent key areas for improvement.

Fidelity Outcomes

Fidelity outcomes by experimental condition are summarized in Table 11, including overall protocol adherence, time-based adherence, and task-based adherence. Mean fidelity scores were highest in condition 3 (mean 70.9, SD 11.4) relative to conditions 1 (mean 58.0, SD 16.5) and 2 (mean 57.5, SD 14.0). Time-based adherence differed across conditions (Kruskal-Wallis χ^2_2=6.7; *P*=.04), with post-hoc comparisons indicating higher adherence in condition 3 relative to condition 1 (*P*.adj=.046). No other pairwise differences were observed.

Table . Fidelity outcomes by experimental condition, including overall fidelity score, time and task-based adherence, and task completion prior to engaging in exploratory behaviors in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

Experimental condition	Values, n	Mean fidelity score (SD)	Time-based adherence, mean (SD) (%)	Task-based adherence, mean (SD) (%)	Completed tasks prior to exploratory behavior, n (%)
Condition 1	10	58.0 (16.5)	69.0 (33.3)	94.6 (4.5)	6 (60)
Condition 2	10	57.5 (14.0)	85.5 (24.1)	93.5 (4.8)	6 (60)
Condition 3	11	70.9 (11.4)	99.1 (15.1)	96.0 (3.7)	1 (9)
Overall	31	62.1 (14.0)	85.0 (27.2)	94.7 (4.3)	13 (41.9)

[a]Between-group differences were assessed using Kruskal-Wallis tests. Time-based adherence differed significantly across conditions (χ^2_2=6.7; *P*=.04; ηH^2=0.222). No significant differences were observed for overall fidelity scores (χ^2_2=5.4; *P*=.07) or task-based adherence (χ^2_2=1.3; *P*=.52).

Task-based adherence remained high across all conditions (mean 94.7%, SD 4.3%). No statistically significant between-group differences were observed for overall fidelity scores (Kruskal-Wallis χ^2_2=5.4; *P*=.07) or task-based adherence (Kruskal-Wallis χ^2_2=1.31; *P*=.52). Although the difference in overall fidelity scores did not reach statistical significance, the *P* value approached the conventional threshold (*P*=.07), suggesting a potential trend toward higher protocol adherence in condition 3 that warrants examination in future adequately powered studies.

Participants in condition 3 were less likely to explore the environment before completing assigned tasks when compared to conditions 1 and 2, suggesting greater adherence to the prescribed task sequence. No significant differences were observed for overall fidelity scores between conditions. Given the exploratory nature of these analyses and small sample size, findings should be interpreted as descriptive.

Tolerability Outcomes

Participants completed the CSQ-VR prior to and following intervention exposure. Conditions 1 and 2 completed the assessment independently, whereas participants in condition 3 were administered the assessment as part of the VR Fitness Assessment conducted by the mock provider. Tolerability outcomes, measured using the CSQ-VR before and after the intervention, are presented by experimental condition in Table 12.

Table . Tolerability outcomes by experimental condition measured using the Cybersickness in Virtual Reality Questionnaire (CSQ-VR) administered pre- and postintervention in a 3-arm randomized feasibility pilot study of virtual reality therapeutics conducted from December 2024 to February 2025[a].

Experimental condition	Values, n	Mean preintervention score (SD)	Mean postintervention score (SD)
Condition 1	10	6.10 (0.32)	6.90 (1.20)
Condition 2	10	6.00 (0.00)	6.20 (0.63)
Condition 3	11	6.73 (1.01)	6.27 (0.90)
Overall CSQ-VR score	31	6.29 (0.69)	6.45 (0.96)

[a]Scores can range from 6 to 42.

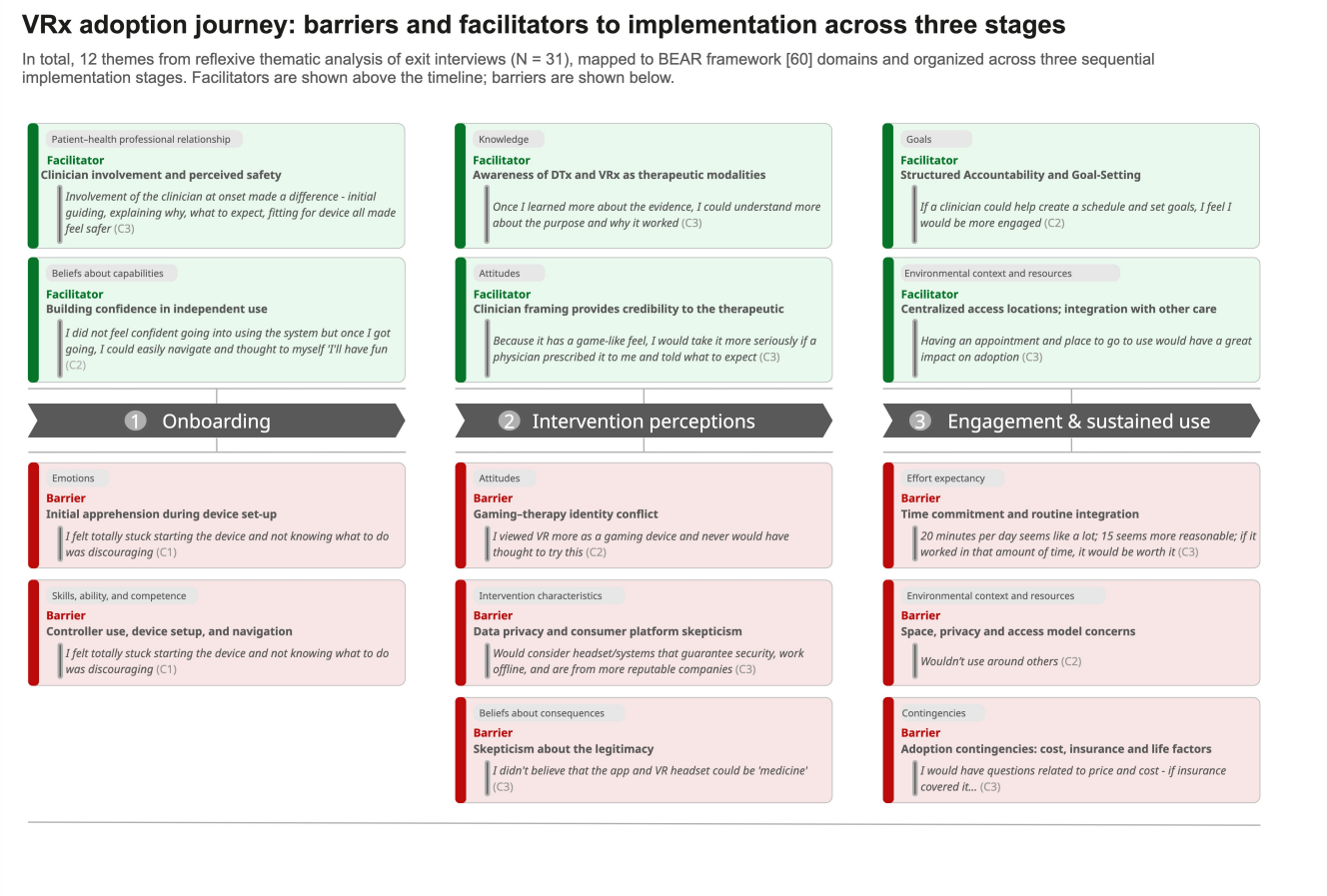
No meaningful increases in cybersickness symptoms were observed following VRx exposure. Mean preintervention symptom scores were low across conditions (mean 6.29, SD 0.69), corresponding to absent to very mild symptoms. Postintervention scores remained similar (mean 6.45, SD 0.96), with no evidence of symptom worsening reported across conditions.

Overall, 74% (23/31) of participants reported no symptoms following the intervention. Among those who reported symptoms, the most common were visual discomfort, dizziness, eye strain, and imbalance or instability. These findings suggest that the VR-based intervention was well tolerated in this sample under the implemented safety and screening procedures.

Qualitative Insights

Qualitative insights are presented according to 14 themes derived from reflexive thematic analysis and mapped to BEAR [60] domains to contextualize implementation-relevant barriers and facilitators. Figure 6 presents key themes organized into 3 stages: onboarding, intervention perceptions, and engagement and sustained use, with representative participant quotes from exit interviews. The full BEAR thematic analysis mapping is provided in Multimedia Appendix 6.

Figure 6. Barriers and facilitators to VRx adoption mapped to BEAR domains across 3 implementation stages. Themes derived from reflexive thematic analysis of exit interviews (N=31). Representative participant quotes are included within each theme card. BEAR: Behavior and Acceptance Framework; C: condition; C1: condition 1 (unguided); C2: condition 2 (self-directed support); C3: condition 3 (provider-supported); DTx: digital therapeutics; VRx: virtual reality therapeutics.



Findings highlight several key factors influencing acceptability, usability, and fidelity. First, emotional responses during onboarding shaped early engagement trajectories. Participants across conditions described initial apprehension, particularly around device setup and controller use, that transitioned into enjoyment and relaxation once interaction with the application began. Participants who engaged in a provider-led consultation (condition 3) expressed higher levels of confidence and reduced uncertainty. Participants who received no support (condition 1) were more likely to describe frustration and discouragement during initial setup. Participants emphasized that the first interaction was a critical adoption threshold, noting that "first touch needs to be positive or people will walk away from using it, especially older people" (condition 1). Provider involvement was consistently identified as the most influential factor in shaping perceived safety, confidence, and motivation during onboarding, with participants describing cybersickness screening, device fitting, and expectation-setting as contributing to a greater sense of comfort and legitimacy.

Perceptions of VRx as a therapeutic modality were strongly influenced by how the intervention was framed and presented. Several participants initially viewed VR as a gaming platform, expressing skepticism about its legitimacy as a health intervention. Provider endorsement as well as evidence-based communication materials shifted these perceptions, with participants noting that professional framing made them take the intervention more seriously. A distinct barrier emerged around identity conflict, in which participants struggled to categorize VRx as medicine rather than entertainment, describing engagement with a game-like interface as therapeutic felt like self-deception without clinical framing.

Concerns related to data privacy and the use of consumer technology platforms for health interventions also emerged, with participants expressing preferences for offline functionality, local data storage, and health-dedicated devices. Limited prior awareness of DTx as a therapeutic modality was common across conditions.

Environmental constraints, such as limited home space, concerns about safety, and apprehension about the immersive properties of VR when others are in the home, shaped preferences for more structured settings and centralized locations where patients can go to use VRx outside of the home. For sustained use, participants emphasized the importance of flexible session length, integration into daily routines, and structured accountability and goal setting. Many expressed that without some form of structure, such as goal setting with providers or progress tracking, they would have difficulty maintaining regular engagement. Participants across conditions raised concerns about the affordability of VR hardware and suggested centralized access models such as clinic-based or community "studios" as alternatives for individual device ownership.

Collectively, these findings highlight the central role of provider involvement, structured onboarding, and contextual fit in supporting adoption and sustained use of VR-based DTx.

Discussion

Principal Findings

This pilot study evaluated 3 implementation strategies for VR-based DTx, comparing unguided use, self-directed use with support materials, and provider-supported use. A single brief exposure to VRx was associated with statistically significant improvements in acceptability across all conditions. However, postintervention acceptance scores remained within the neutral range, suggesting that while perceptions shifted favorably, a single exposure may be insufficient to produce strong endorsement or readiness for sustained adoption.

Differences across intervention conditions were observed in acceptability, usability, and fidelity-related outcomes. Participants receiving provider-led support demonstrated the most favorable and consistent pattern of favorable outcomes, including longer engagement times, higher protocol adherence, and more positive usability ratings. In contrast, self-directed materials produced more variable engagement and, in some cases, appeared to increase cognitive burden during onboarding. Tolerability was acceptable across all conditions, with no meaningful increases in cybersickness symptoms observed. Qualitative findings reinforced the importance of the initial interaction, clinician endorsement, and structured onboarding in shaping early adoption trajectories.

Interpretation of Findings

The findings suggest that early user responses to VR-based DTx are shaped not only by exposure to technology itself but also by the implementation strategy through which that exposure is delivered. While all participants demonstrated improved perceptions of VRx following a single exposure, the differences across conditions indicate that acceptability, usability, and fidelity are strongly influenced by the surrounding implementation approach rather than inherent properties of the intervention alone.

Participants in the provider-supported condition demonstrated the most consistent pattern of favorable outcomes, suggesting that structured onboarding and perceived clinical endorsement reduce uncertainty and increase confidence in use. In contrast, reliance on self-directed materials alone appeared insufficient to support early engagement and may introduce cognitive burden during initial use.

Notably, the disconnect observed between improvements in attitudinal acceptance and more modest shifts in behavioral intention suggests that early exposure may not be sufficient to drive adoption. This reinforces established technology acceptance theories, which suggest that early perceptions may shift quickly, while sustained intention and behavior require continued experience and reinforcement [62]. However, in contrast to prior VR studies that emphasize PU as the primary driver of adoption, our findings suggest that ease of use and structured onboarding may play a more prominent role during initial exposure, particularly for first-time users [79].

Findings in this study align closely with insights from other DTx studies where making DTx feel “ordinary” and familiar accelerated patient adoption and acceptance [42]. In this context, provider involvement and structured implementation strategies may serve as mechanisms that help bridge the gap between initial exposure and sustained engagement.

Role of Provider Support and Human-Centered Implementation

Findings consistently demonstrate that provider involvement plays a critical role in shaping early adoption of VRx. Participants receiving provider-supported onboarding showed greater improvements across acceptability, usability, and adherence outcomes, suggesting that structured human interaction enhances both perceived legitimacy and user confidence. This aligns with broader DTx literature identifying provider endorsement as a critical driver of patient uptake [30,42,80-82]. Our results extend this work by demonstrating that provider involvement influences not only adoption intent but also early usability, engagement, and adherence behaviors during initial exposure.

Provider-led activities, including safety screening, expectation setting, and device setup, appeared to reduce uncertainty and reinforce the therapeutic credibility of VRx. Participants reported greater willingness to engage when the intervention was introduced by a provider, consistent with prior research that provider endorsement enhances perceptions of safety, credibility, and ease of use [28,42,83].

The brief structured nature of the mock consultation suggests that effective implementation may not require a substantial time burden, but rather targeted and well-designed onboarding as part of a familiarization stage. This extends prior research in VR, which found that a familiarization phase before VR exposure reduced surprise effects [84,85]. Future research should evaluate scalable models, including hybrid approaches that combine brief human interaction with digital guidance.

In contrast, reliance on static materials alone was insufficient to support initial engagement. Participants in the self-directed condition relied solely on their own interpretation or ability to digest the information in a timely fashion. The lack of real-time support or personalized guidance may have led to uncertainty or cognitive overload, preventing participants from fully grasping the benefits and ease of using the VR independently. These findings are consistent with other implementation research that found the complexity of the implementation process and the amount of work involved to learn the technologies as barriers for successful adoption [25,86,87]. Future research should evaluate how different types of training delivery (eg, interactive onboarding, human-led instruction, or personalized digital guidance) influence the acceptability of VRx.

Taken together, these findings suggest that structured, human-supported onboarding may reduce early apprehension and improve engagement with VR therapeutics, particularly among first-time users. Provider endorsement remains a powerful lever for uptake, beyond reimbursement or access [88,89]. Notably, the provider interaction observed in this study was brief and structured, suggesting that effective

implementation may not require a significant time burden but rather targeted, well-designed interactions. Future research should evaluate scalable models of clinician-supported onboarding, including hybrid approaches that combine brief human interaction with digital guidance.

Usability Insights

Item-level usability analysis provided granular insights on important barriers to sustained adoption. Participants reported strong intention to use, PEU, and a low perception of system complexity. However, lower confidence, learnability, and a high perceived need for assistance indicate that early usability challenges persist even with implementation support [90].

Compared to other single-exposure VR studies reporting higher usability scores, the slightly lower usability observed in this study may reflect the broader scope of the user experience assessed, from initial device interaction through full session completion, rather than isolated in-app tasks [91]. This more naturalistic approach likely introduced variability reflective of real-world use conditions.

Fidelity and Adherence

A notable qualitative finding was the distortion of time perception during VRx use. Several participants reported that the 20-minute session felt substantially shorter than its actual duration, suggesting a high degree of immersion and cognitive absorption. This aligns with prior research demonstrating the ability of VR to create immersive, attention-capturing experiences that support therapeutic mechanisms such as distraction, presence, and engagement [6,8,92,93]. The relationship between perceived time, immersion, prescription, and clinical outcomes in VRx should be further examined in future studies.

This finding also has important implications for fidelity, as users may be more likely to complete prescribed session durations when the experience feels shorter and more engaging. Related studies on VR use show that the level of immersion may support positive psychological responses, including increased intrinsic motivation, improved mood, and enhanced self-efficacy, which are known contributors to sustained engagement and adherence in rehabilitation and behavioral interventions over time [7,94,95]. Adherence improvements correlate with better clinical outcomes in many DTx studies [30,82]. Further research is needed to show the longitudinal impact of immersion on fidelity and adherence.

Preventing Cybersickness

Cybersickness was minimal across participants and did not appear to meaningfully impact engagement or completion of the VRx session. While a small number of participants reported mild symptoms (eg, slight dizziness or discomfort), these were transient and did not lead to early discontinuation [96-98]. The low incidence of cybersickness in this study may also reflect awareness of the side effect from providing the cybersickness questionnaire prior to use. Cybersickness remains an important consideration for broader implementation, particularly in patient populations who may be more susceptible. Future research should evaluate tolerability over repeated exposures and across diverse clinical populations, as well as identify design and implementation strategies that further mitigate risk.

Scalability and Resource Considerations

The 3 implementation strategies evaluated in this study represent different resource models with important implications for scalability. While provider-supported use produced the strongest outcomes, it introduces additional resource requirements that must be considered in real-world deployment.

The provider interaction in this study was brief (~5 minutes) and delivered by trained personnel, suggesting that effective support may be achievable without substantial burden. In many systems, physicians and psychotherapists act as the main prescribers and gatekeepers, deciding whether DTx are integrated into the treatment pathway [40,43,99]. There is an opportunity for future research to explore alternative delivery models, including nurse-led onboarding, digital-first guidance, or hybrid approaches combining asynchronous support with targeted human interaction.

Participants also identified cost and access as key barriers. Concerns about the affordability of VR hardware and uncertainty around insurance coverage were consistently raised. Suggested solutions included shared-device models, such as clinic-based or community access points, and integration into existing care pathways to reduce both cost and access barriers. Research supports shared-device models, shared digital access, and community or mobile access points as practical, relatively low-cost ways to reduce cost and access barriers, especially when tightly integrated into existing care pathways and supported by appropriate policy and management infrastructure [100-104].

Notably, previous research examining key barriers to DTx adoption showed that improving access to prescriptions and removing cost barriers did not accelerate adoption [34,40,43]. Further investigation found that provider endorsement of DTx significantly impacted patient adoption [43,47]. Adoption of DTx is shaped by intertwined patient, provider, organizational, and regulatory factors [28,42,80,105,106]. Lowering cost or easing prescription alone is insufficient; provider knowledge, trust, workflow fit, and institutional support are central levers for accelerating patient uptake.

While a formal cost analysis was beyond the scope of this study, the relative resource differences across conditions highlight the need for future work evaluating the cost-effectiveness of implementation strategies. Identifying the minimum effective level of provider involvement, as well as opportunities for digital or hybrid onboarding, will be critical for developing scalable models of VRx delivery.

Provider Needs for Implementation

Although provider training was not a primary focus of this study, trained study personnel acting as “mock providers” were able to deliver a brief, structured onboarding interaction that improved perceived safety, usability, and engagement. These materials were designed to be efficient and minimize time burden, addressing a known barrier for provider adoption: limited time during patient encounters [89]. This suggests that

a short "introduce and demonstrate" interaction may be sufficient to support initial adoption without adding substantial time burden to clinical workflows.

Research related to prescribing methods for DTx is limited; methods for prescribing and ensuring patient safety are substantial gaps in how DTx and VRx are delivered today [88,89,107]. There is a substantial opportunity for this research to be expanded on to design simplified tools for patient screening and streamlining the clinical workflow to mitigate adoption barriers experienced by providers. Finally, lightweight screening, dose guidance, and simplified demo devices may further reduce provider friction and support safe, repeatable prescribing.

Theory Integration

This study integrates complementary frameworks to demonstrate that VRx adoption is shaped by the interaction of user perceptions (TAM), usability experience (SUS), and implementation context (BEAR). While brief exposure improved PU and PEU, these shifts did not translate into strong acceptability, indicating that perception alone is insufficient for adoption [61].

Usability findings further highlight a gap between PEU and user confidence, suggesting that initial support may be required even for well-designed systems [64]. The BEAR contextualizes these findings by demonstrating that implementation strategies, particularly through provider involvement, reduce uncertainty and reinforce legitimacy [60]. This reinforces the role of implementation strategies as active drivers of engagement, not simply delivery mechanisms. These findings suggest that successful VRx deployment requires alignment across perception, usability, and implementation strategy to support both initial engagement and sustained use.

Implications

Taken together, these findings suggest that implementation strategy is a critical determinant of early adoption of VR-based DTx. By isolating onboarding and provider support components, this study extends prior VRx research that has largely focused on clinical efficacy to address how these interventions are introduced and supported. The results highlight the importance of integrating structured onboarding and provider touchpoints to enhance usability, engagement, and adherence. These findings have practical implications for the design and deployment of scalable VRx solutions in real-world settings.

Limitations

This study has several limitations that affect the interpretation and generalizability of the findings. First, as a pilot study with approximately 10 - 11 participants per condition, it was not powered to detect between-group differences. As a result, both null and statistically significant findings should be interpreted cautiously, and effect size estimates should be considered exploratory rather than definitive.

Second, multiple comparisons were conducted across TAM and SUS constructs, and exploratory subgroup analyses were performed without correction for multiplicity. While consistent with the exploratory nature of pilot studies, this increases the risk of type I error [69,77]. Accordingly, findings should be interpreted based on overall patterns rather than individual comparisons.

Third, the study was conducted in a controlled, nonclinical sample of healthy adults, which may limit generalizability to intended patient populations. Engagement, motivation, and usability may differ in clinical populations, where symptom burden and provider recommendation play a more central role. There was an imbalance in sex distribution across conditions, with a higher proportion of female participants in condition 3, which also demonstrated the most favorable outcomes. Prior research suggests differences in technology acceptance by sex, and this imbalance may represent a potential confounding variable. Simple randomization was used rather than stratified or block randomization. While baseline characteristics including technology comfort level were monitored across conditions, the absence of formal stratification may have contributed to residual imbalance, including a higher proportion of female participants in condition 3 and uneven distribution of technology comfort level across conditions. Allocation concealment from study personnel was also not implemented, and full blinding of participants and study personnel was not feasible, given the visible differences across study arms. Future adequately powered studies should incorporate formal stratification, allocation concealment, and, where feasible, blinded outcome assessment.

Fourth, provider involvement was simulated and may not reflect real-world prescribing, symptom-driven motivation, or clinical care pathways. In clinical populations, the presence of a diagnosed condition and provider recommendation may further influence engagement, adherence, and perceived value of VR therapeutics.

Fifth, differences between the laboratory and community-based study settings may have influenced usability and engagement. Future studies should evaluate these strategies in fully naturalistic, real-world settings to better understand their impact on adoption and sustained use.

Finally, the study evaluated a single, short-term exposure to VRx, precluding assessment of sustained engagement, long-term adherence, and clinical outcomes. Future research should examine longitudinal use in clinical populations and real-world settings to better understand adoption, adherence, and implementation at scale.

Conclusions

This study provides early evidence that the implementation strategy plays a critical role in shaping the adoption of VR-based DTx. This work is innovative in experimentally isolating implementation components, such as onboarding support and provider involvement, rather than evaluating the therapeutic content alone, which distinguishes it from prior VRx studies that have primarily focused on clinical efficacy. By directly comparing unguided, self-directed, and clinician-supported approaches, this study offers new insight into how implementation design influences early user adoption.

Findings demonstrate that while brief exposure to VRx improved user perceptions across all conditions, structured onboarding and provider involvement produced more consistent

improvements in usability, engagement, and adherence. Notably, even brief provider interaction appeared to increase perceived legitimacy, reduce uncertainty, and support early engagement, suggesting a potential pathway for future scalable implementation through low-burden, hybrid onboarding models, warranting validation in larger studies.

These results contribute to the growing field of DTx by emphasizing that successful deployment depends not only on the technology itself but also on how it is introduced and supported. In real-world settings, integrating lightweight provider touchpoints and structured onboarding may improve uptake and sustained use of VRx interventions. Future research should evaluate these strategies in longitudinal and clinical populations to determine their impact on sustained adherence and clinical outcomes.

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Data Availability

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

Authors' Contributions

AZ, LM, AWK, RK, GM, CM, and LS conceived the study. The study design was a collaboration between all authors. The protocol was written by AZ with input from LM, RK, GM, AWK, CM, and LS. AZ, JF, and CP executed the study and wrote the manuscript. All authors approved the manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1
Preintervention screening instruments and consent forms.
[PDF File, 98 KB - xr_v3i1e90626_app1.pdf]

Multimedia Appendix 2
Description and rationale for selection of OpenBrush.
[PDF File, 341 KB - xr_v3i1e90626_app2.pdf]

Multimedia Appendix 3
Complete implementation package documentation.
[PDF File, 385 KB - xr_v3i1e90626_app3.pdf]

Multimedia Appendix 4
Pre- and postintervention questionnaires.
[PDF File, 211 KB - xr_v3i1e90626_app4.pdf]

Multimedia Appendix 5
Structured participant observation guide and checklist.
[PDF File, 354 KB - xr_v3i1e90626_app5.pdf]

Multimedia Appendix 6

Statistical methods and exploratory analyses.
[PDF File, 258 KB - xr_v3i1e90626_app6.pdf]

Checklist 1
CONSORT 2010 extension for randomized pilot and feasibility trials.
[DOCX File, 29 KB - xr_v3i1e90626_app7.docx]

Checklist 2
CONSORT-eHEALTH checklist (V1.6).
[DOCX File, 25 KB - xr_v3i1e90626_app8.docx]

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Abbreviations

ATT: attitude toward technology
BEAR: Behavior and Acceptance Framework
BI: Behavioral Intention to Use
CONSORT: Consolidated Standards of Reporting Trials
CONSORT-eHEALTH: Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and Online Telehealth
CSQ-VR: Cybersickness in Virtual Reality Questionnaire
DTx: digital therapeutics
IRB: institutional review board
PEU: perceived ease of use
PU: perceived usefulness
REDCap: Research Electronic Data Capture
SUS: System Usability Scale
TAM: technology acceptance model
VR: virtual reality
VRx: virtual reality therapeutics

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