

Design and Implementation of an Interactive VR-Reconstructed ICU System for Psychological Recovery: A Mixed-Methods Pilot Study

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Abstract

Background: More than one-third of intensive care unit (ICU) survivors experience significant psychological impairment, including anxiety, depression, and post-traumatic stress disorder (PTSD). Delusional memories due to unpleasant experiences and lack of contextual understanding are major modifiable risk. We developed an interactive, VR-reconstructed ICU environment integrating multimodal psychological and informational support to facilitate patient-directed exposure therapy and mitigate trauma.

Objective: This pilot mixed-methods study aimed to develop a novel multimodal VR intervention for post-extubation ICU patients and evaluate its usability, feasibility, and preliminary efficacy in improving psychological outcomes and ICU-related memories.

Methods: We enrolled critically ill adults who were first-time ICU admissions, received mechanical ventilation for >48 hours, and were successfully extubated. Participants received a phased, multimodal VR intervention based on the Timing-It-Right framework, tailored to their recovery stage (Stress: <24h, Buffer: 24-48h, Acceptance: 48-72h post-extubation). Outcomes including anxiety (HADS-A), depression (HADS-D), PTSD symptoms (IES-R), and system usability (SUS) were assessed before and after the intervention. ICU memories (ICUMT) were evaluated one week after ICU discharge. Semi-structured interviews were conducted with a subset of participants (n=12) to explore user experience.

Results: Thirty patients completed the study. The VR intervention demonstrated high feasibility, with 185 sessions completed (mean 6.17 sessions/patient, mean duration 7.08 minutes/session). The mean System Usability Scale score was 79.42±7.09, indicating 'good' to 'excellent' usability. Compared to baseline, post-intervention scores showed statistically significant and large reductions in anxiety (mean difference 4.43, p=.032, Cohen's d=1.60), depression (mean difference 5.10, p<.001, Cohen's d=1.90), and PTSD symptoms (mean difference 14.90, p=.013, Cohen's d=1.80). At one-week follow-up, factual memories (48.57±4.72) predominated over emotional (8.97±2.36) and delusional memories (4.70±0.88). Qualitative analysis revealed high acceptance, perceived usefulness in enhancing treatment understanding, and overall positive experiences, despite suggestions for technical refinements.

Conclusions: A theory-driven, co-designed multimodal VR intervention is feasible, acceptable, and shows promising preliminary efficacy for reducing acute psychological distress and promoting adaptive memory recall in ICU survivors. These findings support the conduct of a definitive randomized controlled trial to establish efficacy. Clinical Trial: Registered with the Chinese Clinical Trial Registry on 1 March 2023 under registration number ChiCTR2300068874.

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Original Manuscript

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Abstract

Background More than one-third of intensive care unit (ICU) survivors experience significant psychological impairment, including anxiety, depression, and post-traumatic stress disorder (PTSD). Delusional memories due to unpleasant experiences and lack of contextual understanding are major modifiable risk. We developed an interactive, VR-reconstructed ICU environment integrating multimodal psychological and informational support to facilitate patient-directed exposure therapy and mitigate trauma.

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Results Thirty patients completed the study. The VR intervention demonstrated high feasibility, with 185 sessions completed (mean 6.17 sessions/patient, mean duration 7.08 minutes/session). The mean System Usability Scale score was 79.42 ± 7.09 , indicating 'good' to 'excellent' usability. Compared to baseline, post-intervention scores showed statistically significant and large reductions in anxiety (mean difference 4.43, $p=.032$, Cohen's $d=1.60$), depression (mean difference 5.10, $p<.001$, Cohen's $d=1.90$), and PTSD symptoms (mean difference 14.90, $p=.013$, Cohen's $d=1.80$). At one-week follow-up, factual memories (48.57 ± 4.72) predominated over emotional (8.97 ± 2.36) and delusional memories (4.70 ± 0.88). Qualitative analysis revealed high acceptance, perceived usefulness in enhancing treatment understanding, and overall positive experiences, despite suggestions for technical refinements.

Conclusions A theory-driven, co-designed multimodal VR intervention is feasible, acceptable, and shows promising preliminary efficacy for reducing acute psychological distress and promoting adaptive memory recall in ICU survivors. These findings support the conduct of a definitive randomized controlled trial to establish efficacy.

Trial registration Registered with the Chinese Clinical Trial Registry on 1 March 2023 under registration

number ChiCTR2300068874.

Key words Virtual reality; Psychological recovery; Post-Traumatic stress disorder; Mixed methods

Introduction

Background

Admission to the intensive care unit (ICU) is often a profoundly traumatic experience. More than one-third of critical illness survivors develop persistent psychological sequelae, including anxiety, depression, and post-traumatic stress disorder (PTSD), alongside cognitive and physical impairments[1–3]. A key modifiable risk factor is the formation of distressing and delusional memories during the ICU stay[4,5]. This is particularly relevant for patients admitted in states of coma or under sedation, where the absence of factual recall coupled with unpleasant, illusory experiences significantly contributes to subsequent psychological dysfunction. Mechanically ventilated patients are especially vulnerable, enduring prolonged exposure to stress from critical illness, environmental stimuli, and invasive procedures. Such conditions can precipitate nightmares, hallucinations, memory fragmentation, and delusional episodes, which may evolve into full-blown PTSD and impede recovery[6,7].

Research on fear memory formation indicates that introducing contextual and mitigating information during or after memory recall can modulate the emotional valence of traumatic experiences[8,9]. A promising therapeutic strategy involves real-time positive reframing of ICU experiences to disrupt fear conditioning at an early stage. Delivering psychological support in parallel with medical treatment, initiated as soon as feasible after ICU admission, may help mitigate psychiatric morbidity[1,8,9].

However, healthcare constraints, including resource shortages and uneven distribution, often lead to prioritization of physiological stabilization over psychological support for ICU survivors. Generic, non-personalized interventions are common due to limited patient-specific assessment, and the transition from ICU to general wards is frequently accompanied by reduced nursing support, exacerbating unmet psychological needs[10,11]. Consequently, early and tailored psychological rehabilitation before ICU discharge is crucial for preventing mental health impairments in this population.

Currently, evidence-based preventive strategies for psychological dysfunction in ICU patients remain limited internationally. Existing approaches, such as ICU follow-up clinics[12] and nurse-led interventions[13], have demonstrated variable efficacy. Virtual reality (VR) technology, which creates immersive, computer-simulated environments[14], represents a novel therapeutic avenue. Previous studies have primarily employed nature-based VR scenarios (e.g., mountains, oceans)[15–17]; however, applications within the ICU setting are still emerging. Most interventions have utilized

commercial VR content or recordings of actual ICU environments[18–20], and have been conducted predominantly in regions outside the local context, which may limit their generalizability to certain patient populations.

In this study, we adopted a collaborative design process involving physicians, nurses, patients, and software engineers to develop a multimodal VR support system specifically tailored for ICU patients. Grounded in the Timing It Right framework[21], we established a structured application protocol and conducted a pilot study to evaluate the system's usability, safety, and feasibility. In-depth interviews were performed to explore patient experiences and identify factors influencing the implementation and effectiveness of the VR intervention.

Methods

Study design and setting

This prospective single-arm pilot study employed a convergent mixed-methods design. It was conducted in two general ICUs at the Affiliated Hospital of Zunyi Medical University, a tertiary care hospital in Guizhou Province, China, from September 2023 to January 2024. Inpatients from these ICUs were recruited as study subjects. Using the newly developed ICU multimodal interactive support system as the core intervention tool, a three-day intervention was administered according to the protocol. This quasi-experimental study utilized a pre-post design without a concurrent control group, focusing primarily on evaluating the usability, feasibility, and preliminary efficacy of the VR-based intervention.

Participants

Adult patients (18-65 years) were eligible if they were: first-time ICU admissions, required invasive mechanical ventilation for >48 hours, were successfully extubated, and were alert and able to communicate sufficiently (RASS 0 to +1, GCS $\geq$ 14) post-extubation. Key exclusion criteria included: pre-existing major psychiatric disorders, significant cognitive impairment, severe visual/hearing deficits, history of severe motion sickness, or conditions contraindicating VR use.

Ethical considerations

This study was approved by the Ethics Committee of the Affiliated Hospital of Zunyi Medical University (approval no. KLLY-2022-069) on December 30, 2022. All participation was voluntary. Patients and their primary caregivers were thoroughly informed about the study's purpose, significance, and procedures. Written informed consent was obtained from both patients and family members prior to enrollment. Throughout the study, the rights and privacy of all participants were strictly upheld. In the event of adverse reactions, such as dizziness, vomiting, or any form of discomfort during the use of the system, the intervention was immediately discontinued and

appropriate comfort measures were provided. Participants were free to withdraw from the study at any time without consequence, and their decisions were fully respected.

Intervention

The Multimodal VR Support System was developed by an interdisciplinary team (intensivists, ICU nurses, a psychologist, a psychiatrist, a clinical investigator, and two former ICU patients) based on the Timing It Right (TIR) framework (Figure 1). It comprised four modules: 1) ICU Environment Familiarization, 2) ICU Treatment Education, 3) VR Relaxation & Mindfulness, and 4) Positive Reinforcement Videos. The intervention was tailored to three recovery phases post-extubation: Stress Phase (<24h), Buffer Phase (24-48h), and Acceptance Phase (48-72h)(Figure 2). Participants used a PICO NEO3 head-mounted display. The intervention mode (active self-exploration or researcher-guided passive viewing) was determined collaboratively based on the patient's clinical status and readiness (Table 1).

Figure 1. The multimodal VR support system module

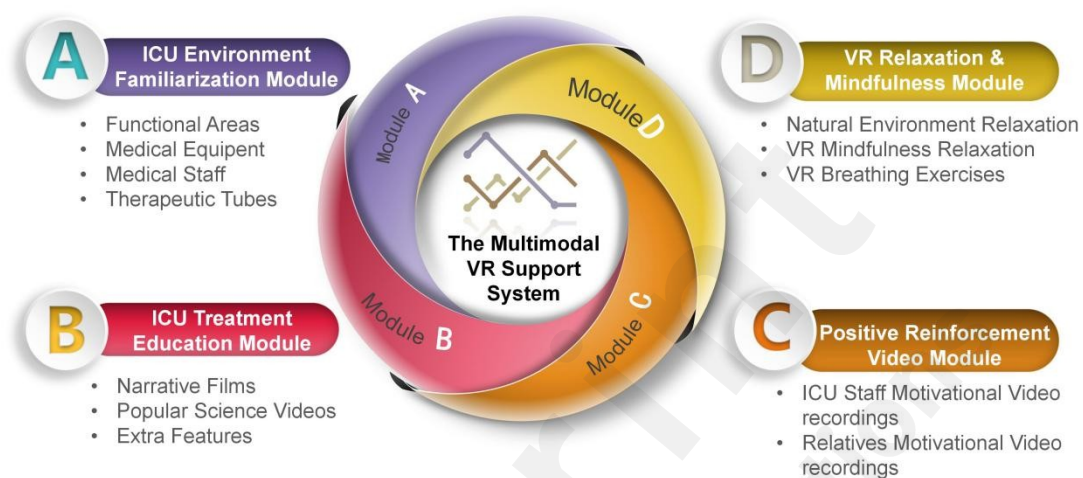


Table 1. System-Based Intervention Content Guided by the Timing It Right

Framework.

Phase & Time	Core Intervention	Primary VR Module(s)	Specific Intervention Content and Format
Frame	Goal		
Stress Phase	Alleviate acute stress	VR Relaxation & Mindfulness Module	(1) Immersive natural environment experience: Patient self-selects calming landscapes (e.g, beach, forest) combined with guided breathing exercises to rapidly reduce anxiety levels.
(Within 24 hours post-extubation)	response, establish a sense of safety		(2) Minimized information input: Provide only essential environmental orientation (e.g, "You are in the ICU, you are safe") to avoid cognitive overload.
Buffer Phase	Actively familiarize	ICU Environment	(1) Interactive environment exploration: Use VR controllers under guidance to interact with virtual ICU equipment and staff, learning about

(24-48 hours post-extubation)	with the environment, rebuild cognitive framework	Familiarization Module ICU Treatment Education Module	their functions and purposes. (2) Selective video learning : Watch educational shorts about therapeutic devices (e.g, "Purpose of the Ventilator," "Tube Safety") based on patient's readiness, utilizing animated explanations to reduce cognitive barriers. (1) Personalized motivational videos : Watch customized encouraging videos from family/medical staff, emotionally resonant with the current recovery stage.
Acceptance Phase (48-72 hours post-extubation)	Deepen treatment acceptance, build recovery confidence	Positive Reinforcement Video Module ICU Treatment Education Module	(2) Personalized treatment process review : Explanation of the patient's individual treatment timeline (e.g, "How you progressed step-by-step out of danger") via video, combined with real-time explanations by staff, to reinforce rational understanding of the treatment. (3) Visualization of recovery goals : Use VR to illustrate phased recovery goals (e.g, "You may try sitting up tomorrow"), enhancing the sense of control.



^a ICU Environment Familiarization: allowed patients to exploratively interact with a virtual ICU environment, ICU staff and medical equipment. ^b ICU Treatment Education: provided 13 professional medical videos covering treatment procedures and nursing operations, supporting cloud-based dynamic updates to the content library. ^c VR Relaxation & Mindfulness: offered an extensive soothing library with up to 100 different scenic views to relax both mind and body, providing a multi-sensory relaxation experience. ^d Positive Reinforcement Video: featured a dynamically updatable encouragement repository, containing motivational videos recorded by the ICU medical team and integrating emotional support recordings from patients' families.

Outcome measures

The primary outcomes included anxiety, depression, and post-traumatic stress disorder (PTSD). Anxiety and depression were assessed using the Hospital Anxiety and Depression Scale (HADS), a validated instrument widely applied in studies involving ICU survivors [22, 23]. The HADS consists of 14 items, with 7 items each for anxiety (HADS-A) and depression (HADS-D). Each item is rated on a 4-point Likert scale (0–3), yielding total scores ranging from 0 to 21 for each subscale. A score of ≥ 8 on either subscale indicates clinically significant symptoms, with higher scores reflecting greater severity: 8–10 mild, 11–14 moderate, and 15–21 severe. This cutoff of 8 offers an optimal balance between sensitivity and specificity for screening.

Subjective distress related to traumatic events was assessed using the Impact of Event Scale-Revised (IES-R), a widely used instrument for evaluating PTSD symptoms in ICU survivors. This 22-item questionnaire is rated on a 5-point scale from 0 (“not at all”) to 4 (“extremely”), with total scores ranging from 0 to 88. A score ≥ 34 was used as the optimal cut-off for probable PTSD [24].

ICU-related memories were evaluated with the ICU Memory Tool (ICUMT), which includes 14 items covering pre-ICU, intra-ICU, and post-ICU recall. Factual memory during the ICU stay was recorded dichotomously [25].

Secondary outcomes

System Usability: Assessed via the System Usability Scale (SUS), a 10-item instrument including both positively and negatively worded items. It comprises two subdimensions: learnability (items 4 and 10) and usability (the remaining 8 items). Higher scores indicate better perceived usability. The scale shows good internal consistency ($\alpha = 0.84$) and content validity (0.879)[26]. Documented adverse events during interventions included falls, unplanned extubation, severe arrhythmia, and oxygen saturation below 88% (Table 2).

Qualitative evaluation

Semi-structured interviews were conducted to explore patient experiences and perceptions. Key interview questions included:

- ☐ How would you describe your overall experience with the system?
- ☐ What psychological or emotional changes did you notice after using the system?
- ☐ What is your evaluation of the content and functionality of the system?
- ☐ What did you perceive as the main benefits or advantages of the system?
- ☐ Were there any limitations or barriers? What improvements would you suggest?

Table 2. Timing of outcome measure assessment

Category	Measure	T1 (Baseline)	T2 (Post- intervention)	Other Assessment Timepoints
Primary Outcomes	Anxiety	✓	✓	
	Depression	✓	✓	
	PTSD	✓	✓	
	ICU-related memory		Assessed 1 week after ICU discharge	
Secondary Outcomes	System Usability		✓	
	Documentation of risk events		Documented after each intervention session	

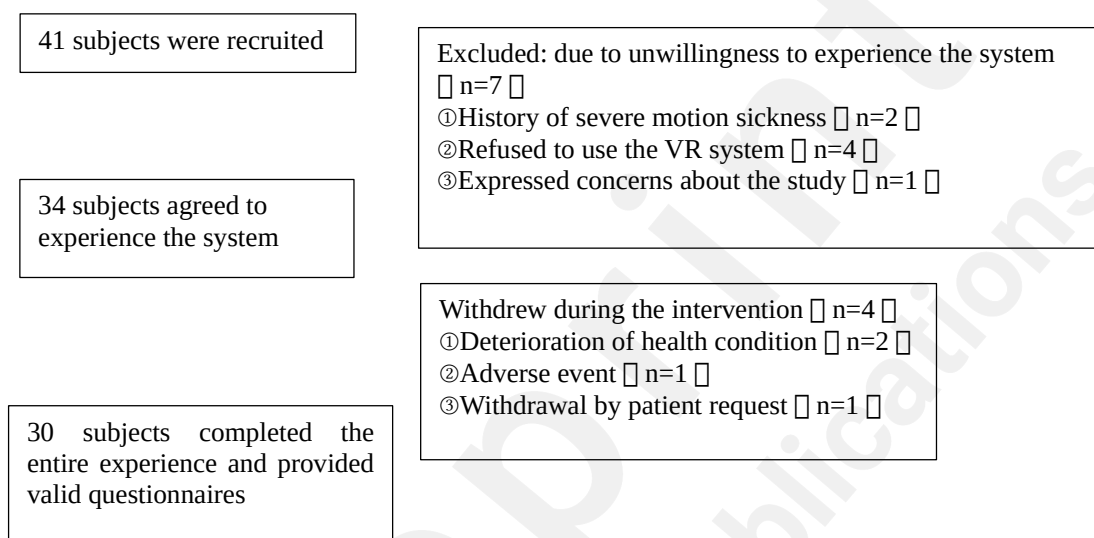
Statistical analysis

Data entry was performed using EpiData software, and statistical analysis was conducted using SPSS version 29.0. Categorical data are described as frequencies and percentages (n, %). The distribution of continuous data was assessed for normality using appropriate tests (e.g. Shapiro-Wilk); normally distributed data are presented as mean $\pm$ standard deviation and non-normally distributed data as median and interquartile range (IQR). For pre-post comparisons within groups, paired t-tests were used for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed data, with exact p-values reported. The significance level was set at $\alpha = 0.05$ (two-tailed). For qualitative data, thematic analysis was performed following the approach outlined by Braun and Clarke. Thematic analysis was performed following the six-phase approach outlined by Braun and Clarke, including familiarization with data, generating initial codes, searching for themes, reviewing themes, defining themes, and producing the report. The sample size was determined based on feasibility objectives for a pilot study rather than formal power calculation, with a target of 30-40 participants to provide initial estimates of efficacy and usability parameters. For statistically significant results, Cohen's d will be computed to assess the effect size.

Results

A total of 41 subjects were recruited in this study (Figure 3). After screening processes and obtaining informed consent, 30 subjects ultimately participated throughout the study and completed the usability evaluation, yielding a participation rate of 73.17%.

Figure 3. Flowchart of subject selection for usability evaluation.



Baseline Characteristics of the Study Participants

A total of 30 patients were included in the analysis of sociodemographic characteristics. The mean age was 42.5 ± 13.77 years, with a male-to-female ratio of 2:1. Participants were all adults aged 65 years or younger. The largest proportion (26.67%) belonged to the 45–54-year age group, while the smallest (13.33%) was in the 18~24-year group.

In terms of educational background, the majority (43.33%) had completed high school or vocational secondary education. With regard to occupation, general employees constituted the largest group (23.33%). Geographically, most participants resided in towns (60.00%), followed by cities (36.67%). Five participants had prior experience with virtual reality (VR). Detailed summaries are provided in Table 3 and Table 4.

Table 3. General information of the study population.

Characteristics	Subgroups	n (%)
Sex	Male	20 (66.67)
	Female	10 (33.33)

Age (years)	18~ 24	4 (13.33)
	25~ 34	5 (16.67)
	35~ 44	7 (23.33)
	45~ 54	8 (26.67)
	55~ 65	6 (20.00)
Marital status	Married	27 (90.00)
	Unmarried/divorced/widowed	3 (10.00)
Literacy	Primary School	5 (16.67)
	Junior high school	8 (26.67)
	High school or junior college	13 (43.33)
	College or above	4 (13.33)
Occupation	Unemployed	6 (20.00)
	Farmer	5 (16.67)
	Laborer	4 (13.33)
	Ordinary workers	7 (23.33)
	Institution staff/civil servants	3 (10.00)
	Freelance	2 (6.67)
	Retired	1 (3.33)
	Student or others	2 (6.67)
	Rural	1 (3.33)
	Urban	29 (96.67)
Mode of payment of medical expenses	Self-financed	4 (13.33)
	Resident Medical Insurance	16 (53.33)
	Employee Medical Insurance	10 (33.33)
Ever used VR equipment	Others	0 (0.00)
	Yes	5 (16.67)
	No	25 (83.33)

Table 4. Clinical data of study subjects.

Item	Grouping	n (%)
Admission to ICU Diagnosis	Respiratory system diseases	5 (16.67)
	Cardiovascular system disease	2 (6.67)
	Digestive system diseases	9 (30.00)
	Blood and hematopoietic system diseases	2 (6.67)
	Trauma / Poisoning	2 (6.67)
	Obstetrics and Gynecology Diseases	8 (26.67)
	Others	
Length of ICU stay (d)	5~9	17 (56.67)
	10~14	9 (30.00)
	15~20	2 (6.67)
	≥21	2 (6.67)
Duration of mechanical ventilation (h)	48~168	23 (76.67)
	169~336	6 (20.00)

	≥337	1 (3.33)
Whether psychological dysfunction occurred	Yes	11 (36.67)
	No	19 (63.33)

1) System usage

Under the guidance of the research staff, 24 patients were able to independently complete the VR experience, while the remaining 6 patients required tailored content delivered via a backend setup for direct viewing.

The total number of sessions reached 185, with an average of approximately 6.17 sessions per patient. The cumulative duration of use was 1,310 minutes, averaging 7.08 minutes per session.

Module-specific interaction data are summarized as follows:

- ICU Environment Familiarization Module: A total of 219 interactions were recorded, including: functional zones (53), medical equipment (71), virtual medical staff (37), and therapeutic tubes (58).
- ICU Educational Videos Module: 133 video views were recorded, categorized as: narrative films (57), popular science videos (64), and extra features (12).
- VR Relaxation Module: 73 sessions were logged across: natural landscapes (45), VR mindfulness (16), and VR breathing exercises (12).

With consent from ICU medical staff and patients' families, a total of 78 encouraging videos were recorded—36 (46.15%) by ICU staff and 42 (53.85%) by family members—with a total duration of approximately 92 minutes.

No system failures, such as crashes or unexpected closures, occurred during the intervention period (Table 5).

Table 5. Interaction/viewing situation of each module.

Theme	Number of Items	Total Interactions/Views	Mean (per Item)
ICU Environment			
Familiarization Module			
Functional Areas	2	53	26.5
Medical Equipent	4	71	17.75
Medical Staff	3	37	12.33
Therapeutic Tubes	7	58	8.29
ICU Treatment Education			

Module

Narrative Films	4	57	14.25
Popular Science Videos	6	64	10.67
Extra Features	3	12	4.00

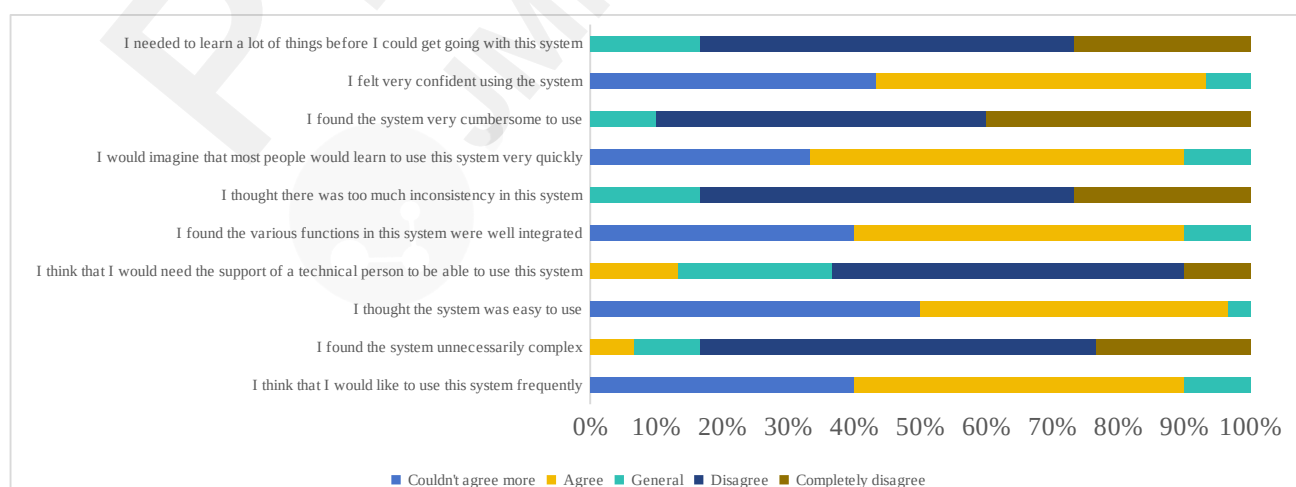
VR Relaxation &**Mindfulness Module**

Natural Environment	4	45	11.25
Relaxation			
VR Mindfulness Relaxation	1	16	16.00
VR Breathing Exercises	1	12	12.00

Positive Reinforcement**Videos Module**

2 System Usability Metrics A total of 30 patients completed the System Usability Scale (SUS). The mean total SUS score was 79.42 ± 7.09 , which falls between "Good" and "Excellent". The usability level is illustrated in Figure 4 .

Figure 4. Detailed responses to the system usability scale (SUS) items.

**3 System safety index**

The patients were closely monitored during the course of this study, and none of them experienced risk events such as bed fall, unplanned extubation, severe arrhythmia, or

oxygen saturation below 88%. However, one patient (3.3%) experienced a mild, self-limiting adverse event during their first VR session. The event was characterized by dizziness and nausea, consistent with visually induced motion sickness. The intervention was discontinued immediately upon the patient's report of symptoms. The symptoms resolved spontaneously without any medical intervention within 30 minutes after headset removal. This patient did not participate in further VR sessions and was subsequently excluded from the efficacy analysis but was included in the safety and feasibility analysis. No other adverse events were reported.

4.1 Patient psychological assessment indicators

Anxiety, depression, PTSD

There was a statistically significant difference in the difference between the patients' anxiety, depression and PTSD scores before and after the intervention ($P < 0.05$), (Table 6). Significant reductions were observed in symptoms of anxiety ($p=0.032$, Cohen's $d=1.60$), depression ($p<0.001$, Cohen's $d=1.90$), and PTSD ($p=0.013$, Cohen's $d=1.80$), indicating large effect sizes.

Table 6. Changes in patient anxiety, depression, and PTSD scores before and after the intervention.

Variable	Pre-intervention (Mean $\pm$ SD)	Post-intervention (Mean $\pm$ SD)	Difference (Pre - Post)	<i>t</i>	<i>p</i>	Effect Size (Cohen's <i>d</i>)
Anxiety	9.97 $\pm$ 3.14	5.53 $\pm$ 2.35	4.43 $\pm$ 3.09	0.392	0.032	1.60
Depression	10.67 $\pm$ 2.59	5.57 $\pm$ 2.76	5.10 $\pm$ 2.09	0.697	<0.001	1.90
PTSD	31.40 $\pm$ 8.67	16.50 $\pm$ 7.82	14.90 $\pm$ 8.71	0.446	0.013	1.80

ICU-Related Memory Assessment

Results showed that after ICU discharge, patients' ICU Memory scores were as follows: factual memory (48.57 $\pm$ 4.72), emotional memory (8.97 $\pm$ 2.36), and delusional memory (4.70 $\pm$ 0.88). Factual memory scored the highest, while delusional memory scored the lowest.

Qualitative Interview Results

Semi-structured interviews were conducted with 12 patients (denoted as H1 to H12) based on the interview outline to gain insights into their authentic evaluations and experiences regarding the system. Demographic characteristics of the participants are presented in Table 7. Analysis and refinement of the interview data revealed three core themes: "User Experience and Perceptions of the System," "Factors Influencing System Use," and "Suggestions for System Improvement."

Table 7. Demographic characteristics of participants in qualitative usability interviews.

ID	Gender	Age (years)	Education Level	Occupation	Prior VR Experience	Usage Mode
H1	Female	22	Junior high	Unemployed	Yes	Independent use
H2	Female	23	Associate degree	Student	No	Independent use
H3	Female	49	Associate degree	Civil servant	No	Independent use
H4	Male	20	High school	General staff	Yes	Independent use
H5	Male	40	Junior high	Worker	No	Independent use
H6	Female	61	Primary school	Unemployed	No	Tailored content delivery
H7	Male	41	Junior high	Self-employed	Yes	Independent use
H8	Male	31	High school	Freelancer	Yes	Independent use
H9	Male	49	Bachelor's degree	Corporate employee	No	Independent use
H10	Female	38	Bachelor's degree	Teacher	Yes	Independent use
H11	Male	51	Associate degree	Engineer	No	Independent use
H12	Male	51	Vocational school	Worker	No	Tailored content delivery

Theme 1: User Experience and Perceptions of the ICU Multimodal VR Support System

1.Perceived Ease of Use

Most interviewees found the ICU interactive health education and emotional support system easy to operate and smooth to use. Patients who used the system independently indicated that initial guidance was necessary, but after instruction, they could adapt to the system quickly, reflecting strong usability.

H2: "I thought it would be complicated and was a bit worried at first, but after the explanation, I knew how to use it."

H4: *“Using the system wasn’t difficult at all; it was very convenient.”*

H5: *“It’s very simple—only two buttons. I picked it up quickly, and it’s pretty fun.”*

H9: *“I thought I wouldn’t be able to handle this high-tech stuff, but it turns out it’s not that hard.”*

2. Perceived usefulness

Participants reported that the system helped alleviate confusion and fear related to unknown medical information. It also served to reduce stress and mitigate the experience of pain.

H1: *“I used to have hallucinations from machine noises and anesthesia—seeing people and animals. At first, I had no idea about my treatment; I only knew the doctors came to give IVs and clean me. But after using the system, everything became clear—where I am and what’s happening.”*

H2: *“After watching, I understood my treatment process. It was moving—thank you to the medical staff. I was confused before and knew nothing. The videos showed me how I was admitted, and the scenery was very relaxing.”*

H3: *“It would be really helpful for those who are nervous or under a lot of stress.”*

H6: *“Watching it somehow made my stomach pain feel less intense.”*

H7: *“When I entered the ICU, I had no idea what was going on and was very worried. The system helped me realize my condition wasn’t as severe, which eased my anxiety. Real medical staff might not explain everything in such detail. At first, everything felt dark—fear made it hard to accept anything. Now I know why machines beep—like when fluids need changing. I even feel more talkative and brighter because I’m less scared and can face things.”*

H9: *“It’s an experience for the eyes—it can heal your mind.”*

H12: *“I knew I was seriously ill but didn’t understand why my kidney stones landed me in the ICU. They mentioned ECMO, which I knew nothing about. The system showed me my treatment journey—how critical I was and what the ICU’s last-*

resort treatments meant. I'm grateful for the warm care from the medical team." 3.

Perceived enjoyment

In most sessions, participants exhibited moderate to high engagement commenting on or reacting to the virtual environment and agreed that the experience felt highly realistic. Those who were more immersed actively interacted with the VR therapy by looking around, pointing or waving at virtual objects and characters, and vocalizing reactions (e.g., "Ooh," "Ah") to scene changes or music. Many participants also described elements of the scene in detail; for example, one noted, "I'd seen it on the news—never expected to experience it myself during an illness." Overall, users reported that the system helped regulate their emotions and found the joystick-based interaction with medical equipment both informative and entertaining.

H2: "This technology is really refreshing."

H4: "I found it quite interesting."

H6: "Never thought at my age I'd get to try something so new."

H11: "I'd seen it on the news—never expected to experience it myself during an illness."

4.Immersion Experience

Interviews revealed significant individual differences in the sense of immersion.

H1: "The ICU layout is okay, not super realistic, but the equipment looks quite similar."

H5: "It feels warmer than the real ICU. I wouldn't dare look if it were the actual place I stayed in."

H8: "I felt no difference from the real ICU."

H9: "Not very similar—a bit fake."

H11: "Pretty good. Once I was in, I forgot about the outside world."

Theme 2: Factors Influencing the Use of the ICU Multimodal VR Support System

1. Sociodemographic Factors: Age, Education, and Prior VR Experience

H1: *“Personally, I think it’s more suitable for younger people. It’s novel and sparks curiosity. Since I’ve used VR before, I adapted quickly. Elderly users might need assistance.”*

H6: *“I’ve never used this before and couldn’t handle the controller. The doctor helped me choose what to watch, which worked well.”* 2. disease and psychological factors

2. Disease-Related and Psychological Factors: Physical Condition and Readiness for Medical Information

H1: *“I wanted to use the system to understand my treatment—otherwise, I felt aimless.”*

H3: *“To be honest, I’ve been feeling unwell and was afraid watching would affect me negatively or worsen my condition. So I only watched my family’s videos and relaxing nature scenes.”*

H4: *“On the first day, my hands weren’t functional enough for the controller. Later, as I recovered, I could use it.”*

Theme 3: Suggestions for Improving the ICU Multimodal VR Support System

1. Technical and Interface Limitations

Users reported cumbersome functionality, low resolution, and inconvenient controller operation.

H4: *“The resolution isn’t very high; some parts are blurry.”*

H6: *“My eyes felt strained after watching for a while.”*

H7: *“It felt a bit restrictive using it while sitting in bed.”*

H8: *“The functions are a bit complicated and overwhelming. I felt a little dizzy but could tolerate it.”*

H11: *“Clicking around with the controller is bothersome.”*

2. VR Equipment Design and Comfort

Users noted that the headset was somewhat heavy and uncomfortable.

H2: *“I wish the device were lighter; it’s a bit heavy.”*

H11: *“The forehead pad is too thick. I was sweating after taking it off.”*

Discussion

This pilot mixed-methods study demonstrates that a novel, multimodal VR intervention, co-developed with clinicians and patients, is both highly feasible and acceptable for use in extubated ICU patients. More importantly, its application was associated with statistically significant and clinically meaningful reductions in symptoms of anxiety ($p=0.032$, Cohen's $d=1.60$), depression ($p<0.001$, Cohen's $d=1.90$), and PTSD ($p=0.013$, Cohen's $d=1.80$). Furthermore, it facilitated a pivotal shift in memory recall, promoting factual memories over distressing emotional and delusional ones, as a recognized key mechanism in preventing PTSD [27-29].

The large magnitude of these effect sizes suggests a substantial clinical impact beyond mere statistical significance, underscoring the potential of this digitally delivered, non-pharmacological adjunct. However, these findings must be interpreted with caution given the pilot design. We propose that these effects are mediated through several synergistic mechanisms grounded in cognitive and neuroscientific theory. First, Cognitive Restructuring and Psychoeducation are facilitated by the provision of clarified, accurate medical information within the immersive VR environment. By allowing patients to visually explore and understand the purpose of frightening equipment and procedures, the system corrects misinterpretations and reduces the sense of threat, thereby directly challenging the foundations of delusional memories [1, 30]. Second, the VR environment serves as a controlled, safe space for Gradual Exposure and Desensitization to ICU-related stimuli. Patients can re-engage with the ICU context at their own pace, which may weaken the conditioned fear response associated with these memories and reduce avoidance behaviors—a core symptom of PTSD [18, 31, 32]. Third, the integration of personalized motivational videos from family and clinicians provides potent Emotional Support and Alleviation of Isolation, likely mitigating feelings of abandonment and fostering a sense of safety and connectedness [33]. Finally, the Attentional Diversion and Pain Modulation afforded by VR's immersive nature engages cognitive resources, diverting focus from nociceptive signals and procedural discomfort, consistent with qualitative reports of pain alleviation and established findings on VR's analgesic effects [17, 34].

Our positive results contribute to a growing yet complex body of literature on psychological interventions in the ICU. While previous studies have explored modalities such as ICU diaries [4, 35], nurse-led consultations [36], and music therapy [37] with varying success, our approach shares conceptual ground with more intensive psychotherapist-led interventions [1, 38] but addresses key barriers of scalability and provider availability. Our findings appear to contrast with the recent multicenter RCT by Vlake et al.[18-20], which reported that a VR-based informational intervention did not alleviate mental health distress among relatives of ICU patients at 6 months. This discrepancy may be explained by fundamental differences: our intervention targeted patients—the direct bearers of traumatic memory—during the critical and malleable post-extubation window, incorporated multimodal strategies (psychoeducation, relaxation, personalized support) rather than

purely informational content, and was administered early (<72h post-extubation), potentially more effectively modulating memory reconsolidation.

The observed enhancement in factual memory consolidation is particularly noteworthy and aligns with the postulated effects of ICU diaries [4], albeit delivered via a more immersive and interactive platform. It supports the theory that introducing corrective information during the labile period of memory reconsolidation can alter the affective valence of traumatic experiences [18, 39]. Furthermore, the alleviation of pain reported by participants underscores the multifaceted benefits of VR, likely mediated through top-down modulation of nociceptive processing.

Our study also contributes to the burgeoning field of digital health by demonstrating a successful model of co-designing a clinically relevant VR intervention with end-users. Unlike many off-the-shelf VR applications, our system was specifically engineered to address the unique psychological challenges of the ICU recovery trajectory. The high usability scores suggest that even acutely ill patients can effectively engage with this form of digital therapy, supporting the feasibility of integrating complex digital interventions into critical care workflows. Future iterations could leverage artificial intelligence (AI) to further personalize content, representing the next step in smart, adaptive digital health solutions for the ICU.

Several limitations of our study must be acknowledged. As noted, the single-arm pilot design without a control group limits the strength of our conclusions. Furthermore, the generalizability of our findings is constrained by the relatively small sample size and the single-center setting. The requirement for patients to be alert and cooperative may have introduced selection bias, potentially excluding those with more severe psychological distress and overestimating the intervention's acceptability. The lack of long-term follow-up data represents another critical limitation; it remains unknown whether the significant reductions in psychological distress and the adaptive memory profiles were sustained beyond the immediate post-ICU period. Future studies must include follow-up assessments at 3, 6, and 12 months to evaluate the durability of these effects and the intervention's true potential in preventing chronic PTSD. Methodologically, while we excluded patients with significant cognitive impairment, this was based on clinical assessment (RASS, GCS); future studies would benefit from the use of standardized cognitive screening tools (e.g., MMSE). Additionally, our thematic analysis, while systematic, would be strengthened in future work by employing multiple independent coders to enhance the reliability of the identified themes. Finally, technical and ergonomic limitations of the VR hardware were identified as areas for future improvement [40].

Despite these limitations, the implications for clinical practice are promising. This project represents among the first initiatives in China to develop a VR-based interactive education and emotional support platform tailored to ICU patients. Unlike commercial VR applications, which often lack clinical relevance, this system was iteratively co-designed with end-users, emphasizing patient-centeredness and usability. By delivering standardized information and emotional support, the system may reduce repetitive clinician workload, streamline communication, and mitigate staff shortages, all while enhancing patient experience. Its scalability and

generalizability support broader implementation within critical care settings, offering a promising adjunct to conventional psychological support strategies.

Conclusions

This study provides robust preliminary evidence that a theory-driven, multimodal VR intervention is feasible, acceptable, and potentially highly efficacious in reducing acute psychological distress and promoting adaptive memory processing in ICU survivors. The large effect sizes observed, coupled with high usability scores and positive patient experiences, strongly support further investigation. A large-scale, multicenter randomized controlled trial is warranted to rigorously evaluate the efficacy of this intervention compared to standard care alone, with long-term follow-up to assess the sustainability of benefits. Future studies should also seek to optimize intervention dosing, identify patient subgroups most likely to benefit, and incorporate health economic evaluations. Should these findings be confirmed, this VR system could represent a scalable and impactful advance in the prevention of psychological morbidity, empowering frontline clinicians to humanize critical care and improve the long-term outcomes of the growing population of ICU survivors.

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Authors' contributions

SJL and ZXJ designed the study. JZ and FC recruited participants and collected the data. GHX and FZ analyzed and interpreted the data. SJL and SSD drafted the manuscript. YL and YY critically revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Affiliated Hospital of Zunyi Medical University (approval no. KLLY-2022-069) on December 30, 2022. All participation was voluntary. All participants gave their informed consent.

Consent for publication

All authors have read and approved the final version of the manuscript and consent to its publication.

Availability of data and materials

The data that support the findings of this study are available on request via the corresponding author ZXJ.

Competing interest

The authors declare no competing interests.

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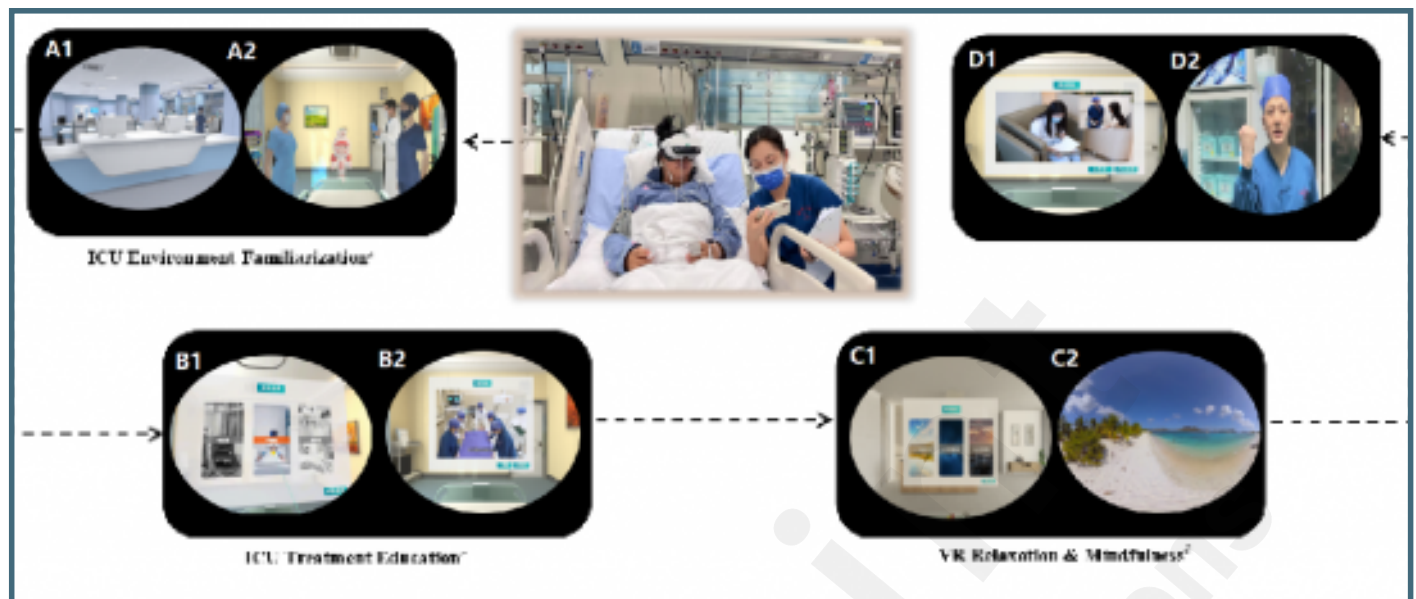
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Supplementary Files

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Figures

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