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ARTICLE

The Impact of Virtual Reality Environment Design on Emotional Recovery: Exploring Factors and Mechanisms

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ABSTRACT: Objectives: Emotional stress is a significant public health challenge. Virtual reality (VR) offers the potential for aiding emotional recovery. This study explores the impact of VR environment design factors on emotional recovery, examining underlying mechanisms through physiological indicators and behavioral responses. **Methods:** Two experiments were conducted. Experiment 1 employed a 4 [Scene Type: real environment (RE), virtual scenes that restore the RE (VR), virtual scenes that incorporate natural window view design (VR-W), and a no-scene control condition (CTL)] × 3 (Experimental Phase: baseline, emotion arousal, recovery) mixed design (N = 33). Participants viewed a 4-min anxiety-inducing video followed by a 3-min scene exposure. State-Trait Anxiety Inventory-State Form (STAI-S), galvanic skin response (GSR), and blood-volume pulse (BVP) frequency were analyzed with linear mixed-effects models. Experiment 2 used a 3 (Motion-control mode: Unnatural, Semi-natural, Natural) × 2 (Sound form: Spatial positioning, Surround) × 3 (Experimental Phase: baseline, emotion arousal, recovery) mixed design (N = 42). Presence was analyzed with the Scheirer–Ray–Hare test; phase efficacy was verified with Friedman tests. **Results:** Experiment 1 showed significant Scene Type × Experimental Phase interactions for GSR ($F = 8.006$, $p < 0.001$, $\eta^2_p = 0.624$) and BVP frequency ($F = 11.491$, $p < 0.001$, $\eta^2_p = 0.704$). VR-W produced the largest recovery ($\Delta GSR = -1.26$; $\Delta BVP = -5.80$; Hedges $g \geq 0.83$) vs. RE and VR. STAI-S returned to baseline across all Scene Types. Experiment 2 revealed main effects of Motion-control mode ($F = 8.55$, $p = 0.001$, $\eta^2_p = 0.32$) and Sound form ($F = 4.35$, $p = 0.044$, $\eta^2_p = 0.11$) on Presence (Semi-natural + Spatial positioning highest). The greatest physiological recovery occurred with the Unnatural Motion-control mode (GSR $H = 20.17$, $p < 0.001$, $\varepsilon^2 = 0.49$; BVP $H = 7.92$, $p = 0.019$), amplified by Spatial positioning Sound form only in this mode. Design factors did not influence STAI-S change. **Conclusions:** VR scenes are as restorative as RE; embedding VR-W accelerates recovery. Maximal Presence is not essential: Unnatural Motion-control mode induced the largest physiological recovery, especially combined with Spatial positioning Sound form.

KEYWORDS: Virtual reality; emotional regulation; presence; physiological indicators; restorative environments; anxiety reduction; multisensory design

1 Introduction

Emotional well-being is a crucial aspect of overall public and psychological health, with its significance increasingly acknowledged on a global scale [1]. Mental health issues associated with emotional well-being, such as anxiety and depression, are becoming more prevalent across various populations and geographic regions [2–4]. A systematic review and meta-analysis conducted in 2021 indicated that the global average prevalence of anxiety and depression is 26.9% [5]. According to the World Health Organization (WHO), approximately 264 million people worldwide suffer from depression, which has become the leading cause of disability globally [6]. Similarly, anxiety disorders affect around 284 million individuals, making it the most widespread mental health condition worldwide [7]. Research consistently shows that untreated emotional disorders contribute to decreased productivity, cognitive impairment, and strained interpersonal relationships [8,9].

Given these challenges, identifying effective methods for regulating emotions has emerged as a critical focus within the public health sector. Among the various approaches, digital media-based interventions, particularly those utilizing virtual reality (VR) technology, have demonstrated promise in enhancing emotional experiences and improving mental health outcomes [10,11]. VR offers users an immersive experience that significantly exceeds the engagement levels of traditional media, such as images or videos. Numerous studies have underscored the potential of VR environments to elicit and regulate emotions, especially in individuals with psychological disorders [12–14]. Felnhofer et al. investigated the emotional responses elicited by five distinct VR scenarios, discovering that each situation effectively triggered corresponding emotional reactions [15]. Furthermore, VR has been effectively employed in treating successfully employed in the treatment of phobias, where patients are gradually exposed to realistic, fear-inducing virtual environments within a controlled therapeutic setting, resulting in substantial improvements [16]. In comparison to traditional treatment methods, the emotional memory retention rate for VR interventions is as high as 68%, whereas the traditional method achieves only 42% [17]. In clinical treatment, Chiesa and Serretti integrated VR into relaxation therapy for individuals experiencing anxiety and depression, reporting significant advancements in emotional regulation [18]. In addition, VR has also been employed to train and enhance emotional regulation skills [19].

Despite the promise of VR environments in clinical settings, relatively little attention has been paid to their potential to aid emotional recovery in the general population. It is critical to explore the specific design factors that contribute to effective emotional recovery within VR systems in order to optimize their use and improve accessibility in public health settings. Previous research by Bohil has identified two primary factors influencing emotional responses in VR settings: the content of the virtual scenes and the user's presence within the environment [20]. Design, as a goal-oriented creative activity that enables precise quantification of the content of a virtual scene, is centered on the systematic translation of ideas into visual solutions for solving a specific problem or realizing an ideal state through the medium of images, models, or language [21]. Chirico et al. found that the introduction of controlled fear or awe stimuli in VR enables comparative analyses of how different content affects emotional intensity and duration, providing empirical evidence for the selection of design elements [22]. VR has also been used to create restorative environments (combining natural landscapes and interactive activities) to alleviate emotional problems such as anxiety and depression [23]. Therefore, the impact on emotional recovery can be explored by designing VR scenario content that incorporates elements of natural landscapes.

Presence is a combination of sensory immersion and cognitive engagement that determines whether a virtual scene is "real" enough to trigger an emotional response [24]. It is not only a core indicator of VR experience, but also a necessary mediator to drive real emotional responses [23]. A high degree of presence can enhance the user's engagement and emotional involvement, and deepen his/her psychological connection with the virtual environment, thus improving emotional recovery [25]. However, different design elements have different effects on the presence, such as spatially localized sound can enhance the sense of space and presence more than ordinary stereo sound, thus enhancing the immersion degree and emotional adjustment effect [26]. On the one hand, as a function of emotional arousal, presence needs to reach a certain level in order to elicit emotions; on the other hand, manipulation of emotions through scene content will elicit more presence [27]. For this reason, we start from the design of virtual scene content, and quantitatively analyze the law of its influence on the presence and emotion recovery by focusing on a variety of design elements, such as natural landscape, spatial positioning sound, and so on. Through systematic experimental evaluation and data analysis, this paper aims to propose actionable design strategies to provide theoretical and methodological guidance for the grounded practice of emotional recovery-oriented VR systems in public health and daily health management.

The present study aimed to elucidate the effects of specific design factors in VR environments on emotional recovery and their mechanisms of action. Experiment 1 compared the differences in emotional recovery between virtual environments based on real scene restoration and traditional static environments, and assessed the facilitating effect of scene design incorporating natural landscape elements on emotional recovery; based on this, Experiment 2 further examined the impact of key design elements that constitute presence on the emotional recovery of a VR scene, exploring which combination of design elements is more effective for emotional recovery in terms of both motion control modes and sound forms. These findings not only have the potential to expand research perspectives on emotional recovery but may also offer new insights into the optimized application of immersive technologies in everyday emotional regulation scenarios, further driving design innovations in VR to promote individual psychological resilience and positive emotional experiences.

2 Literature Review

2.1 Emotional Elicitation and Emotional Recovery

Emotional elicitation methods can be categorized into two primary types: emotional material elicitation methods and emotional situational elicitation methods [28]. Emotional material elicitation involves presenting participants with stimuli, such as images, videos, or other forms of content, specifically designed to evoke particular emotions. For instance, Philippot developed a collection of film materials capable of inducing six predetermined emotions in individuals [29].

Emotional recovery in individuals refers to their capacity to sustain a positive emotional state in the face of negative emotional stimuli or to rapidly shift from a negative emotional response to a more positive one. This ability reflects the individual's resilience in bouncing back emotionally and regaining a positive outlook after experiencing adverse emotional events [30]. Research indicates that negative emotions generally diminish in intensity relatively quickly, often returning to baseline levels within approximately five minutes. In contrast, positive emotions tend to increase in intensity over a short duration. This upward trajectory of positive emotions may be attributed to psychological facilitation, which enhances an individual's overall mood and well-being [31]. Consequently, the onset and recovery processes of negative emotions are often more pronounced and manageable than those of positive emotions, providing a clearer understanding of how individuals respond to emotional experiences.

2.2 Restorative Environment

The mechanism by which the content of VR scenes influences emotional recovery is linked to the concept of restorative environments. Restorative environment theory, introduced by Kaplan and Talbot, refers to environments that promote recovery from mental fatigue and alleviate negative emotions associated with stress. In the context of VR, the content of the scenes plays a crucial role in creating a restorative environment that supports emotional recovery [32]. It is well established that humans have aesthetic preferences for natural elements, which has led to significant research on the restorative effects of natural environments [33–35]. Studies have demonstrated that exposure to restorative environments featuring natural landscapes can result in significant reductions in blood pressure and heart rate [36]. Furthermore, such exposure has been shown to enhance mood and improve attention and focus [37]. Herzog was among the first researchers to highlight the importance of indoor environments in facilitating individual emotional recovery. Specifically, he conducted a study investigating the restorative potential of churches as regular environments frequented by American college students [38]. The evidence strongly supports the idea that both suitable indoor environments and natural settings have the potential to enhance users' moods [39].

The restorative nature of the environment aligns with Ulrich's theory of psychological evolution. According to this theory, human responses to the environment are universal and instinctive, occurring rapidly and without the necessity for conscious cognitive involvement [40]. When specific features are present within the environment, individuals typically exhibit a primary response characterized by a shift toward positive affect. This rapid and positive affective response serves to reduce arousal levels and alleviate stress. The preference for these restorative environments, combined with distancing from threatening stimuli, triggers physiological and psychological changes that initiate a recovery process, facilitating the restoration of emotional equilibrium [41]. The natural environment contains a greater abundance of the aforementioned structural features and elements. Therefore, incorporating natural elements into the design can potentially provide enhanced support for users' emotional regulation [42]. By integrating natural elements into the design of indoor or virtual environments, designers can create spaces that are more conducive to promoting emotional well-being and facilitating effective emotional regulation for users.

Hypothesis H1: *VR scenes incorporating natural elements have better emotional recovery effects.*

2.3 VR Presence Experience Design

Presence is a crucial factor in assessing the efficacy of virtual environment systems [43]. It is commonly regarded as a mental state, representing the subjective experience of being present in a place or environment. This experience is generated through automatic or controlled mental processes and may not necessarily correspond to the actual physical environment in which the individual is physically situated [44]. Draper argued that the attainment of a presence is a consequence of attentional focus. Specifically, when individuals are exposed to a novel and distinct virtual environment, it captures their attention and directs their focus toward a broad range of stimuli within that environment [45]. Witmer et al. proposed that while the novel features of a virtual environment may indeed capture individuals' attention, they primarily serve as facilitating conditions. According to their argument, the acquisition of a presence is primarily dependent on the extent to which individuals receive and transmit stimulus information within the virtual environment. In other words, the immersive and interactive aspects of the virtual environment play a crucial role in fostering a strong presence [24].

From a design standpoint, factors related to the experience of presence in VR can be categorized into control design factors and audiovisual-touch multisensory design factors. Control design factors pertain to the naturalness of user interaction and movement within the VR environment. They can be classified into three mainstream types based on the naturalness of operation: unnatural movement control, natural movement control, and semi-natural movement control. These types reflect the different approaches and techniques used to enable users to navigate and interact with the VR environment in a manner that aligns with their expectations and real-world experiences [46]. Unnatural movement control involves using the controller exclusively to move and adjust the direction of the field of view while remaining stationary in a fixed position. Walking or movement is controlled through buttons or other input mechanisms. Users have the freedom to navigate within the virtual environment using this control method. Natural movement control utilizes locational tracking technology to accurately detect users' spatial positioning within a designated range. Users can move within the virtual environment in a manner that closely resembles real-world movement. Semi-natural movement control combines elements of both unnatural and natural movement control modes. It typically incorporates a combination of control methods to provide users with a more versatile and adaptable means of interacting and navigating within the virtual environment.

Hypothesis H2: *There are differences in the emotional recovery effects of different movement control modes in the VR system.*

In the context of visual-auditory-touch multisensory design, various sensory channels, including visual, auditory, and tactile, serve as avenues for individuals to acquire attentional cues. Different forms of perceptual information can significantly influence an individual's experience of presence. Effective sound design is crucial for enhancing the presence in VR systems. Depending on its presentation, sound can evoke distinct impressions and emotions, exhibiting cross-cultural consistency [47]. The primary modalities of VR sound design include surround sound and spatial positioning sound. Surround sound envelops the user, rotating around their head, while spatial positioning sound accurately conveys the location of sound sources within the virtual environment [48]. Spatial positioning sound associates the sound source with a specific object, whereas surround sound immerses the user in audio from multiple directions. These two sound modalities offer varied user experiences.

Hypothesis H3: *Different sound information designs have an impact on the emotional recovery effects of virtual reality systems.*

3 Experiment 1: Emotional Restorative Study of VR Environment Scenes

3.1 Method

3.1.1 Participants

To ensure the validity and reliability of the experimental results, participants were rigorously screened prior to the experiment. All participants were healthy individuals with normal vision (no correction required) and the ability to adapt to an immersive VR environment. Considering the possibility of motion sickness, the screening criteria included: no significant 3D motion sickness reaction (mild discomfort is acceptable) when wearing an immersive VR headset with visual display functionality for five consecutive minutes, and normal psychological and physiological responses to experimental stimuli, with the ability to cooperate in completing physiological data collection tasks. Ultimately, 33 college students aged 22 to 26 (14 males and 19 females) passed the screening and voluntarily participated in the experiment. All participants had normal mental health and cognitive function, with no history of mental illness or family history. Participants were randomly assigned to three experimental groups (six participants each) and one control group (15 participants). Written informed consent was obtained from all participants prior to the study, and each participant received a compensation of 30 RMB after the experiment. The study was approved by Wuhan University of Technology Ethics committee at the Wuhan University of Technology (IRB number: A2024002). All participants signed the informed consent in this study.

3.1.2 Measures

1. Experimental equipment

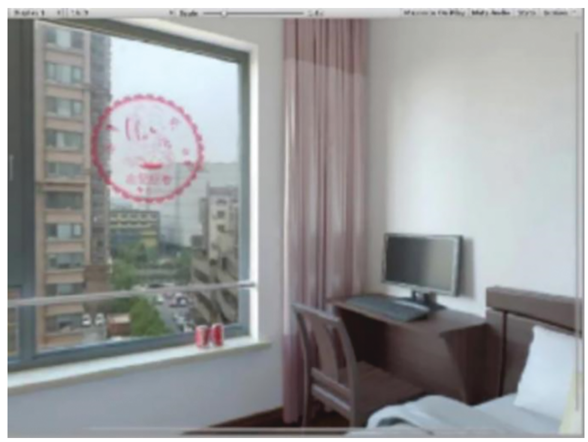
Hardware: HTC Vive kit (HTC Corporation, Taoyuan, Taiwan, China), BioNeuro biofeedback instrument (Thought Technology Ltd., Montreal, QC, Canada), and high-performance computer (CPU: Intel® Core™ i7-11850H; GPU: NVIDIA RTX™ A2000 Laptop GPU, HP Inc., 1501 Page Mill Road, Palo Alto, CA 94304, USA).

Software: Unity 2021.3 LTS (Long Term Support), 3ds Max 2022, and V-Ray 5 for 3ds Max, Update 2.

2. Materials

a. Three types of scenes. A representative real living room environment was selected and a 1:1 virtual environment was constructed as the experimental material, as shown in Table 1.

Table 1: Experimental materials with different levels of independent variables

Title 1 Independent variable display form	Material illustration
1. Real environment	
2. Virtual scenes that restore the real environment	
3. Virtual scenes that incorporate natural window view design	

b. Emotion-eliciting material. We began by referring to previous literature to identify videos that trigger anxiety by searching for the following terms: 'sad videos that make you cry after watching them', 'shocking and scary highway moments caught on camera', and "Top 10 videos that make you feel sad" and selected 10 anxiety-related videos from these [49]. Then, with the help of 30 students (who were not part of the formal experiment), after watching each video, their emotions were rated using a Likert scale from 0 (not at all) to 8 (very strongly). This rating process was designed to assess the emotional arousal effect of the material. Subsequently, the 4-min video clips with the highest emotional ratings were selected as experimental material for the formal experiment.

c. State-Trait Anxiety Inventory-State Form (STAI-S). To assess users' psychological state, we adopted the State-Trait Anxiety Inventory (STAI), a widely recognized psychological measurement tool. The STAI was developed by Charles D. Spielberger et al. in 1970 and translated into Chinese in 1988. It is a 40-item scale. The scale can be used to measure trait anxiety (the degree of anxiety an individual experiences across different times and contexts) and state anxiety (the degree of anxiety an individual experiences at a specific moment), as it includes two independent subscales: State-Trait Anxiety Inventory-Trait Form (STAI-T) and STAI-S, each containing 20 items [50]. This study utilized the STAI-S subscale. The scale is rated on a 1–4 scale, with 1 indicating the lowest level and 4 indicating the highest level of anxiety [51]. Some questions are reverse-scored. State anxiety scores were calculated individually, with higher scores indicating greater levels of anxiety.

3.1.3 Research Design

A 4 × 3 mixed-factor design was used. The between-participants factor was Scene Type with four levels: (1) a real environment (RE), (2) a virtual scenes that restore the RE (VR), (3) a virtual scenes that incorporate natural window view design (VR-W), and (4) a no-scene control condition (CTL). The within-participants factor was Experimental Phase with three levels: baseline, emotion arousal, and emotion recovery.

The dependent variable was emotional response, indexed by both psychological and physiological measures. Psychological reactions were assessed using STAI-S. Physiological indices comprised Blood-Volume Pulse (BVP) frequency and amplitude, galvanic skin response (GSR), and peripheral skin temperature (ST). BVP and GSR, which are regulated by sympathetic nerves, are sensitive physiological indicators of emotional arousal, and are particularly suitable for detecting short-term mood changes [52]. Skin temperature, on the other hand, is affected by peripheral vasoconstriction/diastole, and its level can reflect changes in mood [53].

3.1.4 Experimental Procedure

In the pre-experiment phase, 10 participants were recruited to establish a reference for the specific duration of the experiment and to verify the positive effect of the indoor environment on emotional recovery. Each experiment lasted approximately 30 min, with a stress-relieving phase of 250 s (determined by the longest recovery time of the electrodermal index) as the environment-free recovery experience.

Throughout the formal experiment, changes in physiological indicators were recorded. The experiment consisted of three phases: baseline phase, arousal phase, and recovery phase.

During the baseline phase, participants were instructed to calm down upon arrival at the laboratory and complete the first state anxiety measure.

In the arousal phase, participants watched a 4-min anxiety-inducing video clip and immediately filled out the second anxiety state questionnaire to assess their anxiety levels.

In the recovery phase, the three groups of participants entered either the living room or the laboratory to experience the three different environments in groups. Each environmental experience lasted for 3 min, after which participants completed the state anxiety questionnaire again. The experimental setup is illustrated in Fig. 1.

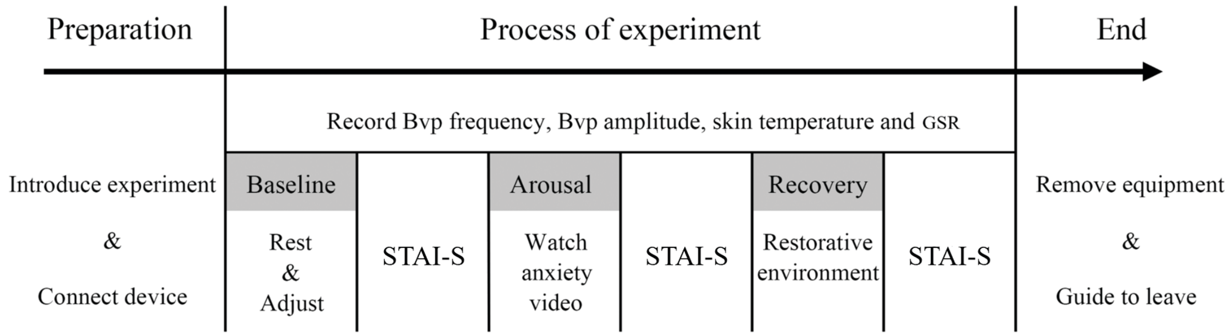


Figure 1: Flow chart of Experiment 1

3.1.5 Statistical Analysis

Prior to inferential testing, all psychophysiological signals were processed to minimise artefacts: GSR traces were baseline-corrected, low-pass filtered and motion artefacts rejected through accelerometer cross-checks, while BVP data were cleaned for ectopic beats and converted to R-R-interval series to derive heart-rate variability; for each phase, the mean of the final 30 s was retained as the analysis value.

Descriptive statistics (mean ± SE) were computed for STAI-S scores and four physiological indices (BVP frequency, BVP amplitude, GSR, peripheral skin temperature). Phase-dependent and scene-dependent changes in the physiological indices were examined with 4 (Scene Type: RE, VR, VR-W, CTL) × 3 (Experimental Phase: Baseline, Arousal, Recovery) linear mixed-effects models, specifying a random intercept for Participant and an unstructured covariance matrix; models were fitted by restricted maximum-likelihood (REML) and Satterthwaite corrections were applied to denominator degrees of freedom. Significant interactions were decomposed with simple-effects analyses, and Hedges g was reported for pairwise contrasts.

State-anxiety scores were analyzed with a 4 × 3 mixed-design ANOVA (SPSS Statistics 25, Type III sums of squares); when Mauchly's test indicated violation of sphericity, Greenhouse–Geisser adjustments were applied. Two-tailed $p < 0.05$ denoted statistical significance, and η^2_p (or Hedges g) quantified effect size.

3.2 Results

In each phase of the experiment, the values of each physiological index were calculated as the mean value of the corresponding data collected during the last 30 s of the phase. This approach allowed for a focused analysis of the physiological responses during the baseline, arousal, and recovery phases. During GSR data preprocessing, baseline correction was performed and combined with accelerometer data to detect motion artifacts and reject abnormal skin conductance response (SCR), followed by removal of high-frequency noise with a low-pass filter, and then smoothing of the signal [54]. BVP data preprocessing was performed and combined with accelerometer data to detect motion-induced disturbances and reject abnormal heartbeat cycles, and the time difference between consecutive R-R intervals was calculated to obtain the heart rate variability time series [55].

3.2.1 . Physiological Indices

Linear mixed-effects models with random intercepts for participants and an unstructured covariance matrix were fitted with Scene Type (RE, VR, VR-W, CTL) and Experimental Phase (baseline, arousal, recovery) as fixed factors. REML estimation and Satterthwaite degrees of freedom were used. Model fit was adequate (e.g., GSR: –2 log-likelihood = 210.04, Akaike information criterion (AIC) = 222.04). Complete test statistics appear in Table 2.

Table 2: Type III tests of fixed effects for physiological indices

Index & effect	F	df (num, den)	*p*	η^2_p
GSR				
Experimental phase	22.841	2, 29	<0.001	0.612
Scene type	1.095	3, 29	0.367	0.102
Phase × scene	8.006	6, 29	<0.001	0.624
BVP frequency				
Experimental phase	220.652	2, 29	<0.001	0.938
Scene type	1.230	3, 29	0.317	0.113
Phase × scene	11.491	6, 29	<0.001	0.704
BVP amplitude				
Experimental phase	70.707	2, 29	<0.001	0.830
Scene type	0.133	3, 29	0.940	0.014
Phase × scene	0.869	6, 29	0.529	0.152
Skin temperature				
Experimental phase	0.384	2, 29	0.685	0.026
Scene type	0.258	3, 29	0.855	0.027
Phase × scene	0.122	6, 29	0.993	0.024

Note: GSR, Galvanic Skin Response; BVP, Blood-Volume Pulse; df, degree of freedom; num, numerator; den, denominator.

1. GSR

The Phase × Scene interaction was significant, F (6, 29) = 8.006, $p < 0.001$, $\eta^2_p = 0.624$ [95% CI = 0.38, 0.75].

Simple contrasts. During arousal, VR (Mean = 4.26) and VR-W (Mean = 4.11) exceeded CTL (Mean = 2.78), $p < 0.001$. From arousal to recovery, the VR-W scene produced the largest drop (Δ = –1.26, SE = 0.32, Hedges $g = 0.83$), significantly greater than RE (Δ = –0.69, $p = 0.006$) and marginally greater than VR (Δ = –0.74, $p = 0.051$).

2. BVP Frequency

Phase × Scene interaction: F (6, 29) = 11.491, $p < 0.001$, $\eta^2_p = 0.704$.

VR-W again showed the largest recovery (Δ = –5.80 bpm, SE = 1.00, Hedges $g = 1.05$), exceeding VR (–3.76 bpm) and RE (–3.09 bpm), Holm-adjusted $p < 0.05$. The main effect of Phase was highly significant, F (2, 29) = 220.652, $p < 0.001$, $\eta^2_p = 0.938$.

3. BVP Amplitude

A robust main effect of Phase emerged, F (2, 29) = 70.707, $p < 0.001$, $\eta^2_p = 0.830$.

Amplitude increased from baseline (Mean = 3.31) to arousal (Mean = 3.88) and partially returned at recovery (Mean = 3.59). Neither the Scene main effect nor the interaction reached significance ($p = 0.529$).

4. Skin Temperature

No fixed effects were significant (largest $F = 0.384$, $p = 0.685$). The mean change from arousal to recovery was −0.10 (95% CI = −0.44 to 0.24), indicating thermoregulatory inertia under the present stressor.

3.2.2 STAI-S

Scores on the STAI-S were analyzed with a 4 (Scene Type) × 3 (Experimental Phase) mixed-design ANOVA, implemented in SPSS 25's General Linear Model (GLM) procedure (Type III sums of squares). When Mauchly's test indicated a violation of sphericity, Greenhouse–Geisser corrections were applied to the degrees of freedom and p values.

Mauchly's test indicated that the assumption of sphericity was violated for the main effect of Experimental Phase, χ^2 (2) = 6.84, p = 0.03. Therefore, Greenhouse-Geisser corrections were applied (ε = 0.82).

The mixed-model GLM revealed a significant main effect of Experimental Phase, F (1.64, 47.67) = 7.20, p = 0.005, η^2_p = 0.20, but no significant main effect of Scene Type, F (3, 29) = 0.87, p = 0.47, η^2_p = 0.08. The Experimental Phase × Scene Type interaction was not significant, F (4.93, 50.00) = 0.91, p = 0.48, η^2_p = 0.09.

Descriptive statistics are presented in Table 3. Bonferroni-adjusted pairwise comparisons showed a marginal rise in anxiety from baseline (Mean = 34.73, SE = 1.39) to emotion arousal (Mean = 37.62, SE = 1.56), p = 0.057. Anxiety then dropped significantly to emotion recovery (Mean = 34.23, SE = 1.25), p = 0.002, with baseline and emotion recovery indistinguishable (p > 0.99), confirming full return to baseline levels.

Table 3: Descriptive statistics for STAI-S (Mean ± SE)

	Baseline	Emotion arousal	Emotion recovery
Overall	34.73 ± 1.39	37.62 ± 1.56	34.23 ± 1.25
RE	36.17 ± 6.31	39.83 ± 5.78	37.67 ± 5.16
VR	34.33 ± 1.63	37.17 ± 1.60	33.50 ± 1.52
VR-W	35.83 ± 3.76	37.33 ± 4.80	35.67 ± 4.08
CTL	32.60 ± 9.65	36.33 ± 10.10	30.07 ± 8.67

Note: Overall, mean across RE, VR, VR-W, and CTL conditions.

Furthermore, there were no significant group differences in state anxiety scores, indicating that subjective reporting of state anxiety reflected the participants' emotional changes but was not sensitive enough to detect differences in different emotionally restorative environments.

4 Experiment 2: Design Study of Emotional Recovery Based on the Presence of VR

4.1 Method

4.1.1 Participants

By recruiting advertisements selected 42 college students to participate in the research, 21 males and 21 females, aged 22–25 years old, were selected to participate in this study according to the same requirements of Experiment 1. The participants were randomly divided into six groups of seven each. The participants were those who had participated in Experiment 1 or other similar experiments. The study was approved by

Wuhan University of Technology Ethics committee at the Wuhan University of Technology (IRB number: A2024002). All participants signed the informed consent in this study.

4.1.2 Measures

1. Measurement equipment

Same as Experiment 1.

2. Measurement tools

STAI-S. Same as Experiment 1.

Presence Questionnaire. This study used the Presence Questionnaire developed by Witmer and Singer. This questionnaire contains 24 items in 7 dimensions, with higher scores indicating a greater presence. The seven dimensions are: Realism, Possibility to Act, Quality of Interface, Possibility to Examine, Self-Evaluation of Performance, Sounds, and Haptic [24]. "Possibility to Examine" refers to the possibility that the user can closely observe objects in the virtual world, and "Self-Evaluation of Performance" is the user's performance self-assessment" is the user's self-assessment of performance in VR. Since the effect of haptic perception was not used in this study, the relevant questions were removed.

3. Experimental materials

Emotion-eliciting material. Same as Experiment 1.

VR scenes. Based on the virtual living room environment in Experiment 1, the VR scenes were designed according to different levels of independent variables, with each virtual scene being a combination of movement control modes and sound forms, as well as scenes without movement control and sound information.

4.1.3 Research Design

A 3 × 2 × 3 mixed experimental design was used, with the independent variables being the mode of movement control (between-participants variable, divided into unnatural movement control, semi-natural movement control, and natural movement control), the form of sound (between-participants variable, divided into spatial positioning sound and surround sound), and the experimental phase (within-participants variable, divided into baseline phase, arousal phase, and recovery phase), which constitute the presence in the design of the VR Experience. Motion control modes are categorized with reference to VR interaction: unnatural motion control (based on joystick controllers), semi-natural motion control (based on indoor system roaming approach) and natural motion control (based on HTC Vive headset suite of devices) [46]. The maximum movement speed of the joystick controllers is controlled to be equal to the average walking speed in real walking and only supports natural movement of about 8 square meters. In the HTC Vive technology, the participant's movement within the HTC Vive is directly mapped (directionally and proportionally) to a point-of-view transformation in the virtual environment, with the direction of viewing decoupled from the direction of walking. The virtual environment is displayed to the participant via a head-mounted display, and the viewpoint is controlled by a vertical bar. The dependent variables were presence and emotional response, where the psychological indicator of emotional response was anxiety and the physiological indicators were specifically BVP frequency and GSR.

4.1.4 Experimental Procedure

The specific procedure in this experiment was the same as that in Experiment 1. After completing the third state anxiety assessment, participants were also required to complete a presence questionnaire.

4.1.5 Statistical Analysis

Presence was evaluated with a 3 (Motion-Control Mode: unnatural, semi-natural, natural) × 2 (Sound Form: spatial-positioning, surround) Scheirer–Ray–Hare extension of the Kruskal-Wallis test, followed by Bonferroni-adjusted pairwise comparisons when warranted. The efficacy of the base-line–arousal–recovery manipulation was confirmed with Friedman tests on GSR, BVP frequency and SAI, with stage-wise Wilcoxon tests for post-hoc contrasts (Bonferroni corrected).

Recovery magnitude for each dependent variable was expressed as the change score d = Recovery − Arousal; effects of design factors on these d values were tested with Kruskal-Wallis tests and a Scheirer-Ray-Hare model. ε^2 or η^2_p provided effect-size estimates. Statistical decisions were based on two-sided tests with $p < 0.05$.

4.2 Results

4.2.1 Presence

Descriptive statistics for each condition are provided in Table 4. A two-way Scheirer-Ray-Hare (SRH) test on the rank-transformed presence scores revealed a robust main effect of Motion-Control Mode, H (2) = 8.55, p = 0.001, η^2_p = 0.32, and a smaller but significant main effect of Sound Form, H (1) = 4.35, p = 0.044, η^2_p = 0.11. The interaction was non-significant, H (2) = 0.82, p = 0.45.

Table 4: Descriptive statistics for presence (rank scores)

Motion-control mode	Sound form	Mean	SD	n
Unnatural	Spatial positioning	17.21	10.06	7
	Surround	12.07	9.01	7
	Pooled	14.64	9.55	14
Semi-natural	Spatial positioning	31.50	9.18	7
	Surround	29.00	7.41	7
	Pooled	30.25	8.12	14
Natural	Spatial positioning	25.64	12.39	7
	Surround	13.57	12.25	7
	Pooled	19.61	13.39	14
Marginal means	Spatial positioning	24.79	11.74	21
	Surround	18.21	12.14	21

Note: Pooled, mean collapsed across the two sound forms within each motion-control mode; Marginal means, mean collapsed across the three motion-control modes for each sound form.

Bonferroni contrasts showed that the semi-natural mode elicited higher presence than both the unnatural mode (Δrank = 15.61, p = 0.001, r = 0.58) and the natural mode (Δrank = 10.64, p = 0.027, r = 0.41); the latter two did not differ. Across modes, spatial-positioning sound produced higher presence ranks (Mean = 24.79) than surround sound (Mean = 18.21, Δrank = 6.57, p = 0.044).

4.2.2 Manipulation Check: Arousal–Recovery Trajectory

Friedman tests confirmed successful induction and partial recovery (Table 5). Stage-wise Wilcoxon tests (Bonferroni-adjusted) were all significant (all $p < 0.001$).

Table 5: Friedman test statistics for GSR, BVP, and STAI-S across baseline, arousal, and recovery phases

Variable	$\chi^2(2)$	p	Kendall W	Mean ranks (Baseline/Arousal/Recovery)
GSR	75.19	<0.001	0.90	1.12/3.00/1.88
BVP frequency	63.05	<0.001	0.75	1.48/3.00/1.52
STAI-S	28.19	<0.001	0.34	1.62/2.67/1.71

Note: GSR, Galvanic Skin Response; BVP, Blood-Volume Pulse; STAI-S, State-Trait Anxiety Inventory-State Form.

4.2.3 Design Factors and Recovery Magnitude

Recovery magnitude was indexed by change scores (d = Recovery − Arousal) for each dependent variable.

1. GSR recovery (d_GSR)

Motion-control mode: Kruskal-Wallis H (2) = 20.17, $p < 0.001$, $\varepsilon^2 = 0.49$ (large). unnatural produced the greatest recovery (mean rank = 33.4), followed by natural (17.1) and semi-natural (14.0).

Sound form: H (1) = 0.34, $p = 0.56$.

A Scheirer–Ray–Hare test on ranks confirmed a large main effect of Motion-control mode, H (2) = 23.68, $p < 0.001$, $\eta^2_p = 0.568$, and a moderate Motion-control mode × Sound form interaction, H (2) = 6.05, $p = 0.005$, $\eta^2_p = 0.252$. Under Spatial positioning sound, unnatural control (Mean = 37.93) was superior to semi-natural (8.14) and natural (15.14); the pattern attenuated under surround sound.

2. BVP frequency recovery (d_BVP)

Motion-control mode: H (2) = 7.92, $p = 0.019$, $\varepsilon^2 = 0.19$; SRH H (2) = 4.53, $p = 0.018$, $\eta^2_p = 0.201$. unnatural > semi-natural (Bonferroni $p = 0.016$).

Sound form and the interaction were not significant ($\eta^2_p = 0.044$).

3. STAI-S recovery (d_STAI-S)

No significant effects of Motion-control mode, Sound form, or their interaction (all $p > 0.42$; $\eta^2_p \leq 0.04$).

5 Discussion

In Experiment 1, Hypothesis 1 was validated, demonstrating that VR scenes incorporating natural elements exhibit superior emotional recovery effects. However, no significant difference was observed between the virtual scenes that recreated the RE and the actual environment regarding their emotional recovery effects. This lack of distinction may be attributed to the highly realistic visual effects of the virtual scenes in replicating the real environment. However, when examining both GSR and BVP frequency, the virtual scene featuring a natural window view demonstrated a superior recovery effect compared to the virtual scenes representing urban landscapes and the actual urban environment [56]. Previous research has indicated that exposure to nature is more effective in reducing cognitive fatigue and promoting emotional recovery than exposure to man-made environments [57]. Thus, the virtual natural-window-view scene may have harnessed the benefits of natural landscapes, resulting in enhanced emotional recovery compared to real environments.

Consistent with our Hypothesis 1, the GSR indicator did differentiate the scenes: VR-W produced the largest drop from arousal to recovery, supporting the notion that electrodermal activity is highly sensitive to rapidly changing restorative cues [58]. Together with the parallel pattern in BVP frequency, this finding suggests that multi-modal autonomic measures converge in highlighting the restorative value of virtual nature. Neither BVP amplitude nor ST differentiated the scenes, indicating that these indices reflect more sluggish or homeostatic processes that were less responsive to the relatively brief VR exposure.

Interestingly, the state anxiety score failed to consistently reflect differences in emotional arousal and emotional recovery functions across the different environments, as observed in the physiological indicators. This discrepancy may be partly attributed to the fact that physiological changes can more subtly and objectively represent autonomic responses to emotional affect [59]. Additionally, physiological indicators provide real-time recordings of emotional changes, whereas state anxiety scores reported afterward reflect participants' emotional states following the experimental manipulation.

The results of Experiment 2 validated Hypothesis 2, which states that different motion control modes in VR systems have different emotional recovery effects, and further revealed a more complex relationship between immersion and emotional recovery: although the semi-natural movement-control mode combined with spatial-positioning sound yielded the highest presence scores, the greatest physiological recovery (d_GSR and d_BVP) emerged in the unnatural movement-control condition. This uncoupling suggests that maximal presence is not a prerequisite for effective down-regulation of stress.

Unexpectedly, virtual scenes that utilized unnatural movement control produced the most pronounced physiological recovery. One possible explanation is that joystick-based locomotion imposes minimal proprioceptive load, thereby reducing vestibular–visual conflict and allowing the autonomic system to settle more quickly during recovery [60]. In contrast, semi-natural and natural movement controls, while increasing ecological validity, may also introduce mild postural or navigational effort that delays full autonomic relaxation.

The influence of sound form [61,62] on the emotional recovery effects of virtual scenes is contingent upon the movement control mode employed. Therefore, this study integrates the original Hypothesis 2 and Hypothesis 3 in Experiment 2 and explores whether different sound information designs under different motion control modes have different emotional recovery effects. Experimental results indicate that the regulatory effects primarily manifest in non-natural control modes: spatial-positioning sound combined with joystick locomotion amplified GSR recovery relative to surround sound, whereas sound form had little influence in the semi- and natural-control modes. These findings further validate Hypothesis 3, and both GSR and BVP frequency capture these design-dependent differences, indicating that heart rate variability is as sensitive as skin conductance activity when movement demands change. It is important to highlight that the effects of different sound forms on emotional recovery in VR are primarily evidenced by GSR, while changes in BVP frequency were not significantly different. This discrepancy may arise from the fact that BVP frequency serves as a more stable overall measure of emotional state, whereas GSR indicators are more responsive to variations in stimuli [63,64].

It is interesting to note that neither the movement control mode nor the sound form showed significant differences in subjective anxiety indicators. Some researchers have suggested that the differences in recovery effects produced by VR design may not be sufficient to directly influence subjective emotional feelings related to anxiety. Instead, physiological changes and autonomic responses to emotional affect can provide more subtle insights into the emotional state of individuals, which aligns with the findings of this study [59].

However, other researchers have explored the effects of sound quality, sound information, and sound localization on users' subjective emotional evaluations. They have found that behaviorally relevant ecological sounds can have a more significant impact on users' subjective emotions [63,64]. Therefore, when designing the sound form in VR experiences, it may be beneficial to incorporate ecological sound information that can generate feedback sound effects such as footsteps and door-closing sounds. Additionally, in cases where sound sources cannot be precisely positioned, surround sound can be employed to allow users to perceive environmental sounds from any position, thus enhancing the emotional atmosphere of the VR environment.

Our findings provide valuable insights into how VR technology can effectively aid individuals in their journey toward emotional well-being and resilience. By understanding the impact of VR design elements (e.g., natural landscapes and spatially-located sounds) on emotional recovery, it was validated that individuals can benefit from immersive virtual environments that promote relaxation and rejuvenation [65]. Furthermore, our study sheds light on the specific mechanisms underlying emotional recovery within VR environments, paving the way for the development of targeted interventions and experiences. Individuals who face emotional stress and seek solace can find practical guidance in utilizing VR systems that prioritize effective design factors. This research fosters a greater understanding of the interplay between VR design elements, user experiences, and emotional regulation, offering a roadmap for the advancement and refinement of VR technology in the domain of emotional well-being.

This study has several limitations. Firstly, the subjects in this study were primarily college students whose preferences for the content of VR scenarios may be group-specific, limiting the generalizability of the findings; future research should expand the diversity of the participant group to enhance the external validity of the findings. Secondly, existing VR scenes mostly rely on visual and auditory stimuli, while sensory feedback technologies such as touch, smell, and temperature and humidity are not yet mature, and these factors may weaken the presence and emotion regulation effects, and more factors can be further explored in the future to investigate the effects on emotion recovery. Furthermore, public perceptions and understandings of risks are important [66], and subsequent studies could investigate how the VR system might be leveraged to reduce anxiety among the public when confronted with risks. Finally, the dissociation we observed between physiological recovery and self-reported anxiety underscores a measurement limitation: subjective scales may lack sensitivity to subtle design manipulations. Future work should incorporate finer-grained affective reports or ecological momentary assessment to bridge this gap.

6 Conclusions

Currently, many individuals are struggling with negative emotions that significantly affect their well-being. Our research seeks to identify tools that promote emotional recovery by integrating VR with restorative environments. Additionally, we explore the design elements and mechanisms of VR environments that contribute to emotional recovery. This study has the potential to improve the effectiveness of emotional recovery strategies for individuals facing mental health challenges.

In summary, this study shows that highly realistic VR scenes can evoke an emotional recovery effect comparable to that of their real-world counterparts and that incorporating natural features such as sky, trees, and water further enhances recovery—especially when presented as a window-view inside otherwise urban settings. Presence remains a useful predictor of emotional recovery, but our data reveal that maximal presence is not strictly required for the greatest physiological benefit. Movement-control mode proved critical: contrary to our initial hypothesis, the unnatural (joystick-based) control yielded the largest GSR and BVP recovery, whereas semi-natural and natural controls produced smaller—but still significant—benefits. Sound information also shaped outcomes, but its influence was mainly evident when joystick control was used; spatial-positioning sound in that context amplified recovery compared with surround sound, while sound form had little effect in more embodied control modes. Taken together, these findings highlight that design factors affecting sensorimotor load (locomotion, spatial audio) interact with scene content to determine how quickly the autonomic system returns to baseline. Designers should therefore tailor control schemes and audio rendering to the intended restorative goal rather than assuming that the most "natural" option always produces the strongest benefit.

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