

## Virtual therapeutic landscape: An immersive intervention for anxiety in university students

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Anxiety among university students has become a critical global public health issue due to its high prevalence and impact. This study builds on prior work on virtual therapeutic landscape design and evaluation by operationalising therapeutic landscape principles in a virtual reality setting, aiming to develop and evaluate a multi-sensory immersive intervention for anxiety relief. Drawing on semi-structured interviews and the analytic hierarchy process, four core components – sensory, interactive, personalised and content experience – were identified, forming a systematic evaluation framework. A within-subject pre–post study involving 46 university students demonstrated that short-term virtual therapeutic landscape exposure significantly reduced state anxiety ( $p < 0.001$ ,  $d = 0.916$ ), negative affect ( $p < 0.001$ ,  $d = 0.588$ ) and enhanced subjective vitality ( $p < 0.001$ ,  $d = 0.966$ ). Physiological data showed decreased phasic skin conductance response and phase-related changes in tonic skin conductance level across baseline–intervention–recovery, both showing significant time effects. By contrast, virtual therapeutic landscape exposure produced comparatively smaller changes in trait anxiety ( $p < 0.001$ ,  $d = 0.739$ ) and positive affect ( $p = 0.005$ ,  $d = 0.437$ ). Taken together, virtual therapeutic landscape yielded convergent psychological and physiological benefits and provides an empirically grounded extension of therapeutic landscape theory into digital mental health interventions.

### *Implications for practice or policy:*

- Universities could use virtual therapeutic landscape as a low-burden adjunct to support short-term anxiety relief in students.
- Student support services can position virtual therapeutic landscape as a brief intervention for reducing state anxiety and negative affect rather than as a substitute for longer-term treatment.
- Designers of virtual reality mental health interventions should prioritise sensory immersion, user-friendliness and system stability to improve restorative outcomes.

**Keywords:** anxiety, university students, virtual therapeutic landscape (VTL), electrodermal activity (EDA), digital mental health interventions, mixed methods

## Introduction

In recent years, anxiety has emerged as a major focus of global public health research, particularly among university students, a population especially vulnerable due to increasing social competition, intensified academic demands and growing employment pressure (Werner-Seidler et al., 2021). This group experiences multiple academic stressors, such as heavy workloads, peer competition and the pursuit of excellence, and non-academic challenges, such as financial difficulties, homesickness, social adjustment issues and sleep disturbances (Cheung et al., 2020). A global study estimated prevalence rates of depression, anxiety and sleep disorders among university students at 34%, 32% and 33%, respectively (Deng et al., 2021). Sustained anxiety correlates with reduced academic engagement, diminished participation in extracurricular activities and adverse outcomes such as insomnia, impaired concentration, fatigue and, in severe cases, physical illness or suicidal behaviour (Moskow et al., 2024; Ridley et al., 2020). Approximately 75% of lifetime mental disorders manifest before the age of 24 (Kessler et al., 2005), and anxiety disorders typically emerge during the transition from adolescence to early adulthood (Pine et al., 1998), highlighting the urgency of developing scalable, low-burden interventions that fit into students' daily routines.

Within this context, therapeutic landscape (TL) theory offers a promising framework for alleviating anxiety and improving mental health among university students. TL involves the purposeful design and utilisation of natural environments to promote health and well-being (Bell et al., 2018). Extensive research indicates that exposure to vegetation, flowers and water bodies supports physiological recovery and psychological restoration (Doughty et al., 2023). In rehabilitation settings, natural landscapes facilitate human–nature interaction, enhance mental health and yield recovery benefits influenced by individual landscape preferences (Li & Liu, 2024). Scientifically arranged campus landscapes can also foster psychological restoration (Wang et al., 2023). However, universities often face financial constraints, land scarcity and high maintenance demands, limiting the large-scale deployment of high-quality TL.

Virtual reality (VR) technology provides a viable alternative to deliver TL-consistent experiences without the spatial or physical constraints of landscapes. VR enables immersive, multi-sensory simulations of natural environments, offering visual and auditory stimuli that can trigger restorative responses (Bell et al., 2024). Evidence from mental health interventions shows that virtual nature exposure reduces anxiety through integrated sensory stimulation (Li et al., 2021) and enhances emotional resonance via physiological recovery mechanisms (Kumpulainen et al., 2024). Drawing on this evidence, we conceptualised virtual therapeutic landscape (VTL) as a VR-mediated environment designed to deliver the restorative features of TL through immersive media, thereby overcoming the limitations of physical implementation.

This study, building on our prior work, which established the VTL factor structure and validated the design model (Cui et al., 2026), operationalised the VTL framework in an implementation-oriented spherical video-based virtual reality (SVVR) protocol by identifying key design elements through thematic analysis and the analytic hierarchy process (AHP; Braun & Clarke, 2006; Vaidya & Kumar, 2006), using a weighted evaluation system and creating an SVVR experience. The experiment comprised a 3-minute baseline, 5-minute exposure and 3-minute recovery, balancing immersion with low interaction load and high ecological validity. Alongside the pre–post self-reported measures, we further examined phase-resolved electrodermal activity (EDA) responses (baseline–exposure–recovery) to provide psychophysiological triangulation. Psychological outcomes were measured using the state–trait anxiety inventory (STAI; STAI–S/STAI–T; Spielberger, 1971), the subjective vitality scale (SVS; Ryan & Frederick, 1997) and the positive and negative affect schedule (PANAS; Watson et al., 1988), which were analysed with paired-samples *t* tests. Physiological outcomes were recorded using EDA, including skin conductance response (SCR) and skin conductance level (SCL), and analysed with repeated-measures ANOVA (RM-ANOVA). This framework links theory, design and empirical testing, offering a methodological basis for scalable applications, with the overall research workflow and methodological framework summarised in Figure 1.

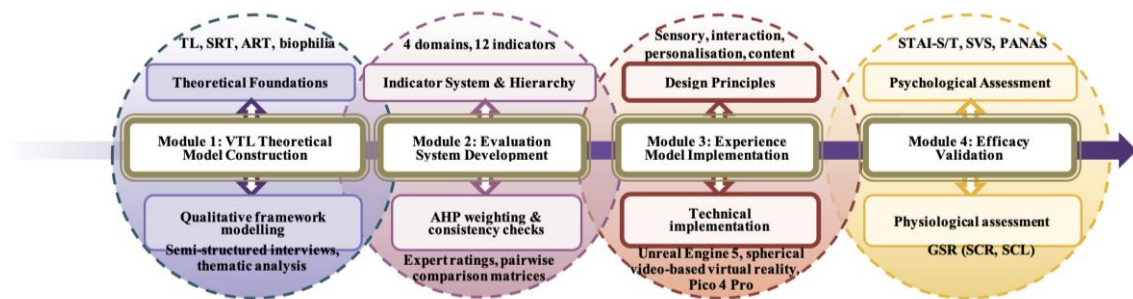


Figure 1. Research workflow and methodological framework of the VTL study

## Literature review

### TL theory and its relevance to university students

TL theory conceptualises health-promoting places as integrated configurations of physical, social and symbolic attributes that afford psychological restoration and well-being (Gesler, 1993; Williams, 1998). Grounded in environmental psychology, TL is supported by stress reduction theory (SRT; Ulrich, 1983) and attention restoration theory (ART; Kaplan & Kaplan, 1989), which explain restorative effects through rapid psychophysiological down-regulation in response to benign natural cues and the replenishment of directed attention via environmental qualities such as being away and soft fascination. These mechanisms align with the biophilia hypothesis, emphasising humans' evolved affinity for nature (Wilson, 2017), and are consistent with empirical findings showing that vegetation, water bodies and coherent spatial structures can alleviate negative affect and improve mood (Coventry et al., 2021). In university contexts, campus landscape preference and configuration have been linked to recovery outcomes, suggesting a design-sensitive dose–response relationship particularly relevant for university students (Lee & Koo, 2018; Wang et al., 2021).

### Operationalising TL theory via SVVR

Grounded in the restorative framework of TL theory, VR provides a robust technological means to reproduce the physical attributes of natural restorative environments within immersive and experimentally controlled settings. A substantial body of empirical research on VR-based nature exposure has demonstrated its effectiveness in reducing state anxiety, enhancing subjective vitality and improving affective states, with presence and immersion frequently identified as key mediating mechanisms (Frost et al., 2022; Mattila et al., 2020; Ünal et al., 2022). Among various VR modalities, SVVR offers unique advantages for translating TL theory into practical interventions. By delivering 360° spherical video mapped onto a surrounding sphere, SVVR achieves high immersion, a wide field of view and strong ecological validity. Empirical SVVR interventions in higher-education settings have reported improvements in learning performance and reductions in domain-specific anxiety, including writing anxiety (Hsu, 2025). Furthermore, a meta-analysis has indicated that SVVR yields overall positive effects on cognitive and non-cognitive learning outcomes, with effect sizes moderated by instructional design and implementation features (Wu et al., 2024). SVVR, when experienced via a head-mounted display (HMD), further enhances sensory immersion by delivering spatially synchronised, close-proximity visual and auditory cues, which in turn intensify the sense of presence (Shi, 2024). Its standardised and reproducible presentation of natural scenes reduces development costs, minimises inter-study variability and lowers control demands, thus mitigating participant fatigue and cognitive overload. Based on these methodological strengths, the present study adopted SVVR technology as the VR modality for implementing VTL interventions in a rigorously controlled experimental context.

### Current limitations in VTL research and study objectives

Despite these promising findings, VTL – a VR-mediated environment explicitly embedding TL constructs – remains relatively under-represented in the literature. Although TL constructs have been translated into

measurable indicators and their relative importance has been quantified using AHP, evidence remains limited for integrating such evaluation with physiological measures within a unified and theoretically grounded protocol, and existing validation has relied largely on psychometric and user-reported outcomes (Cui et al., 2026). Moreover, the methodological pathway for translating these indicators into a reproducible and implementation-ready VTL experience model remains insufficiently specified. Research focusing specifically on university students is particularly scarce, with prior work tending to emphasise the technical implementation of VR or the conceptual design of TL, while giving insufficient attention to psychophysiological convergence and implementation-level validation for VTL interventions.

To address these gaps, this study aimed to (a) apply a scientifically valid evaluation factor system for VTL to ensure feasibility and intervention effectiveness in practical applications; (b) examine the effects of VTL on alleviating anxiety symptoms among university students and the mechanisms underlying psychological regulation; and (c) evaluate the comprehensive effects of VTL on university students across psychological and physiological outcomes.

## **Construction and weight evaluation of the VTL design strategy theoretical model**

### **Methods**

#### *Qualitative construction of the VTL design strategy theoretical model*

This study employed semi-structured interviews, guided by environmental psychology theories (Van den Berg & Staats, 2018), to examine university students' needs and preferences for VTL (Adeoye-Olatunde & Olenik, 2021). Specifically, ART informed prompts on attentional recovery such as "What kinds of places help you clear your mind?", and SRT informed prompts on stress alleviation such as "Which natural elements in a virtual environment help you feel less stressed?", ensuring that item generation mapped onto empirically supported restorative mechanisms. Based on this framework, the interview content was further refined with feedback from experts in environmental psychology, VR technology and related fields.

Additionally, a small-scale pilot test was conducted to assess the clarity, relevance and wording of the interview questions. Participants generally found the questions clear and the environment conducive to discussion, but noted that some theoretical terms were overly abstract and a few items overlapped in content. In response, terminology was simplified and redundant questions were removed to improve comprehensibility and focus for the main study. Interviews took place in a quiet and comfortable setting, with sessions lasting approximately 40–55 minutes. Open-ended prompts were used to capture participants' intuitive impressions, emotional responses and overall evaluations of VTL features.

Textual data were analysed using thematic analysis (Braun & Clarke, 2006), following six phases: familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes and producing the report. NVivo software was employed to facilitate coding and theme development. Ultimately, the core elements of VTL design were identified, providing the basis for the development of the theoretical model for VTL design strategies.

In terms of sample selection, this study recruited 18 university students from a comprehensive university in Zhejiang Province, China, through online recruitment, with ages ranging from 18 to 24 years and a gender distribution of 50% male and 50% female, as shown in Table 1. Participants' academic backgrounds covered engineering, humanities and art and design disciplines, ensuring diversity across fields. The study was reviewed and approved by the Ethics Committee of Zhejiang University of Finance and Economics Dongfang College, and all participants signed informed consent prior to the interview.

Table 1

*Demographic and background information of semi-structured interview participants*

Item	Category	No. of participants (n = 18)	Percentage (%)
Age	18–20 years	8	44.4
	21–24 years	10	55.6
Gender	Male	9	50.0
	Female	9	50.0
Study field	Science and technology	6	33.3
	Art and design	8	44.4
	Humanities and social sciences	4	22.2

*Quantitative weight evaluation of the VTL evaluation factor system*

Based on the interview results, this study used AHP (Vaidya & Kumar, 2006) to conduct a quantitative analysis of the importance of VTL design elements, thus constructing an evaluation factor system. We invited eight experts with extensive experience in environmental psychology, VR technology, immersive storytelling, landscape architecture and related domains to participate in the evaluation.

A multi-level hierarchical model of VTL design factors was established, comprising goal, criteria and sub-criteria levels. The experts conducted pairwise comparisons using the standard AHP 1–9 scale, and the resulting pairwise comparison matrices were used to calculate factor weights. The maximum eigenvalue ( $\lambda_{max}$ ) and corresponding eigenvector (W) were obtained to derive the weights of each factor. A consistency check was performed using the consistency index (CI) and consistency ratio (CR), where  $CI = (\lambda_{max} - n) / (n - 1)$  and  $CR = CI / RI$ ; only matrices with  $CR < 0.10$

Finally, IBM SPSS Statistics was used to calculate weights for each expert, and a geometric mean was applied to obtain the final weights for all indicators. This process resulted in a multi-level factor system for evaluating VTL design.

**Analysis and results***Results of the VTL design strategy theoretical model*

As shown in Figure 2, this study first identified initial codes through coding of the interview content (e.g., landscape richness, tactile authenticity, exploratory interactivity). In the second phase, these initial codes were categorised into higher-level subthemes, such as visual quality, auditory quality and tactile quality, corresponding to the sensory-experience dimension of VTL. In the third phase, themes were defined and named, yielding four core themes: sensory experience, interactive experience, personalised experience and content experience.

Building upon this thematic structure, the VTL design strategy theoretical model provides a conceptual framework that elucidates the interconnected mechanisms of VTL design. This is demonstrated through (a) enhancing sensory experience by optimising visual, auditory and tactile qualities to promote immersion; (b) strengthening interactive experience by improving interaction richness, system stability and user-friendliness to ensure effective engagement; (c) advancing personalised experience through personalisation quality, device compatibility and immersion to support adaptive and individualised VR use; and (d) enriching content experience by emphasising narrative quality, cultural–educational value and aesthetic value to facilitate emotional resonance.

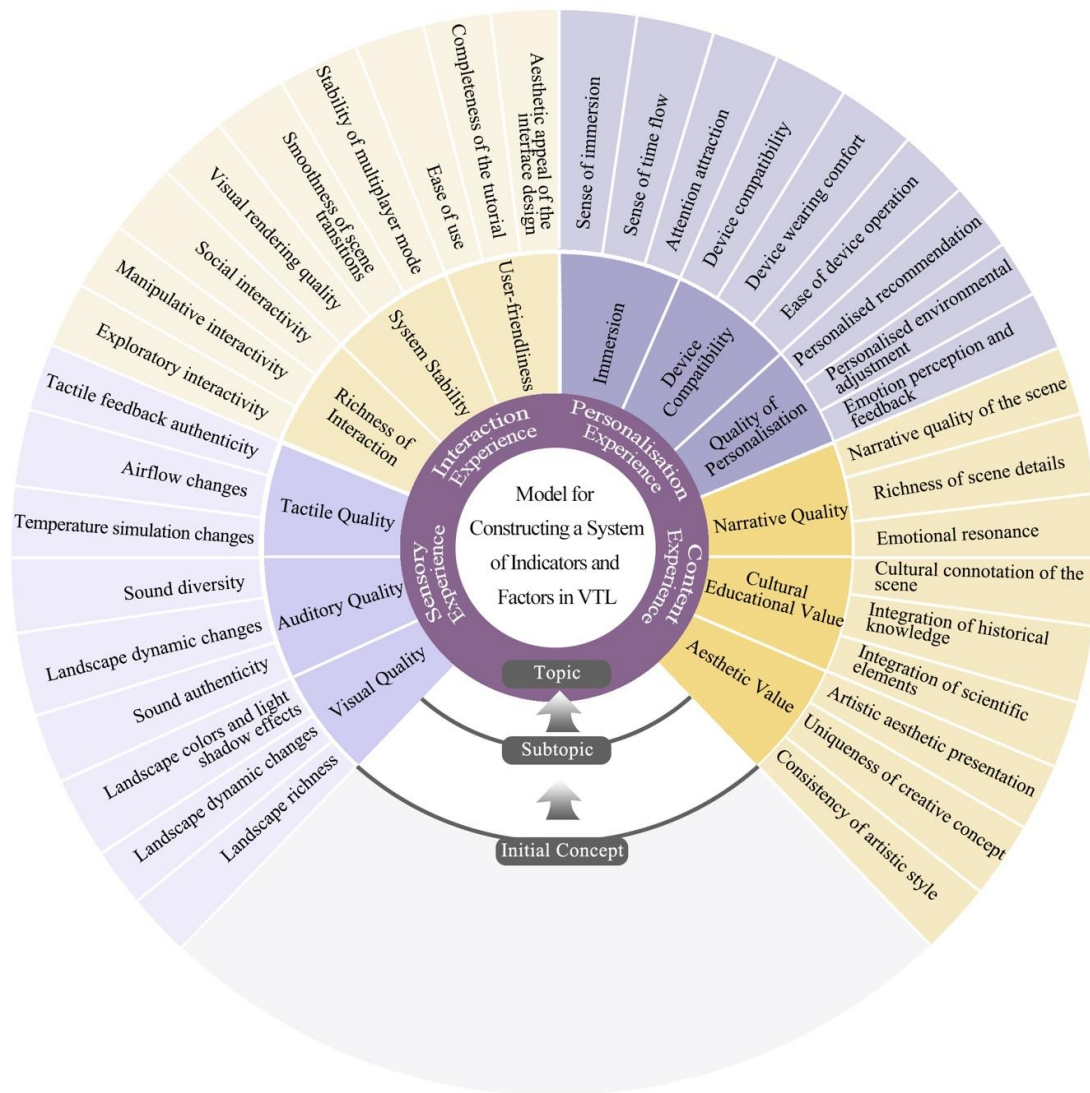


Figure 2. Summary of themes for the theoretical model of VTL design strategies  
 Note. Adapted from Cui et al. (2026, Figure 3), *Digital Health*, <https://doi.org/10.1177/20552076251412624>. Licensed under CC BY-NC 4.0. Redrawn.

**Analysis of weighting results for the VTL evaluation factor system**

This study structured the VTL experience design factors into a three-level hierarchical model: goal level (A) defined as “providing the most effective VTL experience”; criteria level (B) consisting of sensory (B1), interactive (B2), personalised (B3) and content experiences (B4); and sub-criteria level (C) with 12 key indicators, such as visual quality (C1), auditory quality (C2) and tactile quality (C3).

Eight experts conducted pairwise comparisons of the criteria and sub-criteria levels to construct pairwise comparison matrices, which were tested for consistency ( $CR < 0.10$ ). IBM SPSS Statistics was used to calculate the matrix's  $\lambda_{max}$ , CI, CR, eigenvector and weight vector. The weight results were then aggregated using a geometric mean to derive the final global weights of each evaluation indicator, as presented in Figure 3.

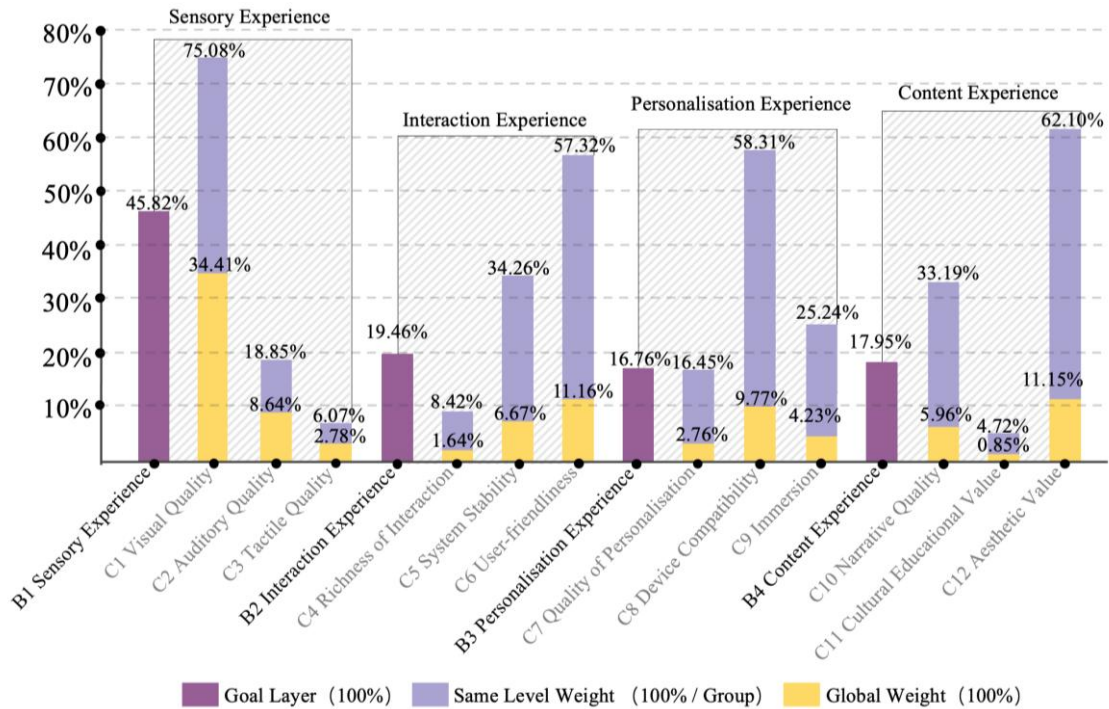


Figure 3. Weighting results for the VTL evaluation factor system based on the eight-expert AHP evaluation

By visualising the weight results of the VTL evaluation factor system, the study revealed meaningful differences in the relative importance of evaluation indicators for VTL experience design. Within the VTL evaluation system, the analysis of criteria-level factors highlighted the varying contributions of different design elements to participants’ restorative experience.

The research results showed that sensory experience dominated with a global weight of 45.82%, highlighting the core role of multi-sensory immersion in VTL design. Among these, visual quality ranked first with 75.08% of the sensory experience weight, emphasising the importance of high-fidelity visual effects in participants’ immersive experience. Auditory quality accounted for 18.85% of the sensory experience weight and played an important role in creating emotional resonance and environmental atmosphere. Although tactile quality had a weight of only 6.07%, its potential in enhancing immersion and improving the participant experience warrants further exploration.

Interaction experience, with a weight of 19.46%, ranked second, highlighting the key role of smooth and rich human–machine interaction in enhancing therapeutic effects. The analysis showed that user-friendliness is the core factor in interactive experience, accounting for 57.32%, emphasising the importance of simple and intuitive interface design in reducing participants’ operational costs. System stability followed closely with a weight of 34.26%, indicating that performance optimisation is critical for maintaining immersion, while interaction richness accounted for 8.42%, showing that although its weight is relatively low, its potential to enhance participant interaction through innovative design should not be overlooked.

Content experience, with a weight of 17.95%, ranked third, emphasising the importance of narrative and artistry in virtual therapeutic recovery. Aesthetic value held the highest proportion within this dimension at 62.1%, highlighting its crucial role in enhancing visual appeal and overall engagement in virtual therapeutic environments. Narrative experience quality accounted for 33.19%, enhancing participants’ sense of immersion and emotional resonance through scenario construction and interactive storytelling. Although the weight of cultural and educational value was relatively low (4.72%), it still played a positive role in enriching the educational and cultural content of the virtual scenes.

Personalised experience, with a weight of 16.76%, ranked fourth at the criteria level, emphasising the need for device compatibility during participants' VTL experience. Device compatibility (58.31%) dominated, reflecting the core role of hardware design in enhancing immersion and user experience. Additionally, immersion and personalisation quality accounted for 25.24% and 16.45%, respectively. These results suggest that, along with improvements in hardware performance, dynamic adjustments and personalised services are crucial for further optimising participants' restorative experience.

## **VTL development and implementation**

### **VTL experience model development**

Grounded in the established theoretical framework and weighted evaluation index system, the VTL experience model was systematically developed to operationalise four principal domains: sensory experience, interaction experience, personalisation experience and content experience. This design ensured that key indicators and their relative weights were consistently integrated into both the system architecture and scenario design.

For sensory experience, the model placed particular emphasis on the realism and immersion of visual, auditory and tactile modalities. Visual quality was achieved through the integration of high-fidelity natural landscapes, dynamic lighting, shadow effects and seasonal variation. Auditory quality was enhanced by spatialised synchronisation of environmental sounds – such as birdsong, wind and water – with visual stimuli, thereby reinforcing ecological authenticity. Although direct tactile feedback was not provided, both the virtual scenario and the physical experimental environment were controlled to maintain a temperature of 22–24°C, relative humidity of 50–55%, and well-circulated air. This environmental control further strengthened the sense of presence and physical comfort.

In terms of interaction experience, the VTL model was designed to maximise user-friendliness and system stability by employing an intuitive, streamlined interface. The richness of interaction was deliberately limited to reduce operational complexity and cognitive load, thereby increasing accessibility and ensuring a seamless and reliable user experience.

For personalisation experience, the model emphasised device compatibility and personalisation quality by supporting a wide range of mainstream VR headsets and enabling individualised hardware calibration. Users could also adjust environmental parameters, such as brightness and sound volume, according to their preferences. Moreover, the ability to freely adjust the viewing angle within the 360° scene by rotating the headset further contributed to immersion and provided users with flexibility in controlling their visual perspective.

With respect to content experience, the VTL model was structured to highlight aesthetic value and narrative quality. The virtual environment featured dynamic elements like animal activity, together with diverse natural landscapes and ecological features of aesthetic significance, exemplified by seasonal changes and nuanced rendering of light. This design was intended to foster emotional resonance, enhance aesthetic appreciation and support psychological restoration.

### **Technical implementation and system description**

As illustrated in Figure 4, the VTL system was implemented using SVVR on the Pico 4 Pro headset, featuring dual 2.5 K resolution displays and a 90 Hz refresh rate for high-definition, low-latency visual output. Developed in Unreal Engine 5 with a modular software architecture, the VTL platform ensures compatibility with mainstream VR devices and efficient, stable scene rendering. SVVR content comprised 360° spherical videos mapped onto a surrounding sphere and presented through the HMD to provide synchronised visual and auditory cues, thereby enhancing immersion and presence. The user interface was streamlined to minimise interaction load and standardise operation, and the overall configuration was designed for robust, reproducible and stable deployment in immersive psychological research.



Figure 4. Real-life photo from VTL experience and 360° scene presentation in the HDM  
 Note. The 360° virtual scene was developed in Unreal Engine 5 using the third-party environment asset Nordic Conifer Biome (Pixelgoat Store, Epic Games Fab/Unreal Engine Marketplace) under the Standard License.

## Empirical research and analysis of VTL experience

### Methods and materials

#### Experimental subjects and research preparation

Participants were recruited via online voluntary sign-up from a comprehensive university in Zhejiang Province, China. Of the 65 students who registered, 60 completed the pre–post psychometric assessment; 51 consented to concurrent EDA recording; and 46 provided complete paired psychometric and EDA data for the present analyses. A priori power analysis using G\*Power for a paired-samples *t* test (medium effect, Cohen’s *d* = 0.5;  $\alpha$  = 0.05; power = 0.80) indicated a minimum of 34 participants. Participant characteristics are shown in Table 2.

Table 2  
 Participant demographics and VR experience

Item	Category	No. of participants ( <i>n</i> = 46)	Percentage (%)
Age	18–20 years old	24	52.2
	21–24 years old	22	47.8
Gender	Male	23	50.0
	Female	23	50.0
VR experience	With VR experience	6	13.0
	Without VR experience	40	87.0

The final sample consisted of 24 individuals aged 18–20 years (52.2%) and 22 individuals aged 21–24 years (47.8%), with a balanced gender distribution (50% male, 50% female). Regarding VR familiarity, six participants (13%) reported prior experience, whereas 40 participants (87%) had no relevant background. Prior to participation, they were fully informed about the study procedures and signed a written informed consent form, and all study procedures were reviewed and approved by the Ethics Committee of Zhejiang University of Finance and Economics Dongfang College. Against this backdrop, psychological and physiological testing were conducted simultaneously on all 46 participants, enabling a multidimensional assessment of the effects of VTL.

Regarding inclusion and exclusion criteria, individuals with a self-reported history of migraine, motion sickness, epilepsy or vestibular disorders were excluded to reduce the risk of VR-induced discomfort. Prior to the formal experiment, participants were verbally screened for adaptability to immersive VR environments to ensure safety and minimise the risk of participant withdrawal. To further minimise the influence of individual differences, all participants received standardised instructions and completed a brief VR acclimation session before the intervention.

### Experimental design

This study employed an integrated experimental design combining psychological and physiological assessments to examine the effects of VTL on anxiety, vitality and emotional states among university students. Self-reported outcomes were collected immediately before and after the VR session (pre and post). Participants underwent a three-phase procedure, including a 3-minute resting baseline, a 5-minute immersive intervention and a 3-minute post-intervention recovery. In parallel, EDA was recorded continuously across baseline, intervention and recovery, enabling triangulation of subjective change with phase-resolved autonomic dynamics during and after immersion. Meanwhile, autonomic nervous system activity was continuously monitored using the PTES100 wearable physiological acquisition system (PsychTech, China). The PTES100 was worn on the wrist to enable continuous EDA recording throughout all phases. EDA recording was initiated prior to the baseline period and continued uninterrupted until the end of the recovery period; phase-wise analyses were conducted by segmenting the continuous signal according to the predefined experimental timing. Photographic documentation of the acquisition setup is provided in Figure 5. The primary physiological signal collected was EDA, a widely used indicator of sympathetic nervous system activity and stress-related arousal (Boucsein, 2012). Specifically, two EDA-derived measures were extracted: SCR, reflecting short-term phasic arousal, and SCL, reflecting tonic sympathetic activation.



Figure 5. PTES100 wristband placement and data acquisition terminal

The assessment of anxiety levels was conducted using the STAI (STAI-S/STAI-T), which distinguishes between temporary state anxiety and long-term trait anxiety and is widely used in psychological research (Spielberger, 1971). Psychological vitality was assessed using the SVS, a sensitive instrument for detecting short-term changes in vitality (Ryan & Frederick, 1997). Emotional state was assessed using the PANAS, which independently evaluates positive affect (PA) and negative affect (NA), enabling bidirectional assessment of PA enhancement and NA reduction (Watson et al., 1988).

During the VTL intervention, the laboratory environment was maintained at 22–24°C, relative humidity at 50–55%, with well-circulated air. Physiological signals were continuously recorded across all three phases to capture autonomic nervous system activity. Before the baseline phase, participants completed the psychological scales to establish pre-intervention measures. They then underwent a baseline period during which resting-state physiological data were recorded, followed by the 5-minute VTL exposure delivered through a Pico 4 Pro HMD. The 5-minute exposure duration was determined a priori based on previous studies, ensuring sufficient immersion while avoiding fatigue or cognitive load (Suppakittpaisarn et al., 2023). This brief and standardised exposure enhanced internal validity and minimised potential confounders such as scene variability or participant fatigue (Cullen et al., 2021). After the exposure, participants entered the 3-minute recovery phase while physiological data collection continued.

Immediately after completing the entire three-phase procedure, participants completed the same psychological scales again. By comparing pre- and post-exposure data, the study evaluated the psychological and physiological effects of the VTL experience.

**Data processing and statistical analysis**

Psychological scale data were first screened for normality using the Jarque–Bera test (skewness and kurtosis). When normality was supported, pre–post differences were examined using paired-samples *t* tests; otherwise, non-parametric alternatives were considered. Effect sizes were reported as Cohen’s *d* to quantify the magnitude of within-subject change. For physiological outcomes, RM-ANOVA was used to test phase effects in EDA across baseline, intervention and recovery. Sphericity was assessed with Mauchly’s test, and Greenhouse-Geisser corrections were applied when violations occurred.

**Data analysis and results**

**Psychological results**

In the final analytic sample (*N* = 46), paired-samples *t* tests were conducted on pre–post scores for all psychological scales. Summary statistics and test results are presented in Table 3.

For anxiety, STAI-S decreased from 43.54 to 37.43 with  $t(45) = 6.214, p < 0.001$  and  $d = 0.916$ , which corresponds to an approximate relative reduction of 14.03%. STAI-T decreased from 45.74 to 42.07 with  $t(45) = 5.012, p < 0.001$  and  $d = 0.739$ , an approximate relative reduction of 8.02%. The effect size was larger for STAI–S ( $d = 0.916$ ) than for STAI–T ( $d = 0.739$ ), consistent with a stronger acute impact on transient anxiety states.

Subjective vitality improved substantially. SVS increased from 23.00 to 26.09 with  $t(45) = -6.551, p < 0.001$  and  $d = 0.966$ , which represents an approximate relative increase of 13.43% and a large effect at the scale level, consistent with an immediate energising influence of the immersive exposure.

A differential pattern was observed for affect. PANAS-PA increased from 39.72 to 42.57 with  $t(45) = -2.963, p = 0.005$  and  $d = 0.437$ , corresponding to an approximate relative increase of 7.18%. PANAS-NA decreased from 31.70 to 26.63 with  $t(45) = 3.991, p < 0.001$  and  $d = 0.588$ , corresponding to an approximate relative reduction of 15.99%. Taken together, these findings suggest that short-term exposure preferentially modulates momentary states such as vitality and state anxiety and is more effective at down-regulating negative affect than up-regulating positive affect.

Table 3  
*Integrated psychological effects of the VTL intervention*

Scale or dimension	Pre <i>M</i>	Post <i>M</i>	Difference	<i>t</i> (45)	% Δ	<i>p</i>	Cohen's <i>d</i>
STAI – S	43.54	37.43	6.11	6.214	-14.03%	< 0.001**	0.916
STAI – T	45.74	42.07	3.67	5.012	-8.02%	< 0.001**	0.739
SVS	23.00	26.09	-3.09	-6.551	13.43%	< 0.001**	0.966
PANAS-PA	39.72	42.57	-2.85	-2.963	7.18%	0.005**	0.437
PANAS-NA	31.70	26.63	5.07	3.991	-15.99%	< 0.001**	0.588

*Note.* %Δ = 100 × (Post – Pre) divided by Pre; positive values indicate relative increases after the intervention and negative values indicate relative decreases. *t*(45) denotes a *t* value with 45 degrees of freedom (*df* = *N* – 1 for paired tests with *N* = 46).

\**p* < 0.05; \*\**p* < 0.01; Cohen’s *d* small effect: 0.20 ≤ *d* < 0.50, medium effect: 0.50 ≤ *d* < 0.80; large effect: *d* ≥ 0.80.

**Physiological results**

To investigate the physiological effects of the VTL intervention, RM-ANOVA was performed separately on SCR and SCL across three time points: pre-intervention (baseline), mid-intervention and post-intervention. As shown in Table 4, Mauchly’s test of sphericity indicated that the assumption was violated for both

indicators (SCR:  $W = 0.530, p < 0.001$ ; SCL:  $W = 0.162, p < 0.001$ ), so Greenhouse-Geisser corrections were applied ( $\epsilon_{SCR} = 0.680$ ;  $\epsilon_{SCL} = 0.544$ ).

Table 4  
Mauchly's test of sphericity and epsilon corrections for SCR and SCL

Index	Mauchly's $W$	$p$	Greenhouse-Geisser $\epsilon$	Huynh-Feldt $\epsilon$
SCR	0.530	< 0.001	0.680	0.694
SCL	0.162	< 0.001	0.544	0.547

Note. Greenhouse-Geisser and Huynh-Feldt  $\epsilon$  values are reported for sphericity corrections. Greenhouse-Geisser correction was applied in both cases because Mauchly's test was significant ( $p < 0.05$ ).

As shown in Table 5, SCR showed a significant main effect of time,  $F(1.361, 61.223) = 19.953, p < 0.001$ , partial  $\eta^2 = 0.307$ . The average SCR values decreased significantly from pre- ( $M = 0.056, SD = 0.079$ ) to mid- ( $M = 0.035, SD = 0.066$ ) and further to post-intervention ( $M = 0.023, SD = 0.046$ ), indicating reduced phasic sympathetic arousal, which is consistent with anxiety relief. According to conventional benchmarks for partial  $\eta^2$  (small = 0.01, medium = 0.06, large = 0.14), this represented a large time effect.

Conversely, SCL also showed a significant time effect,  $F(1.088, 48.974) = 9.856, p = 0.002$ , partial  $\eta^2 = 0.180$ . As illustrated in Table 5, the mean SCL increased from pre- ( $M = 1.393, SD = 1.149$ ) to mid- ( $M = 1.779, SD = 1.639$ ) and post-intervention ( $M = 1.985, SD = 1.996$ ). The VTL intervention produced an upward SCL trend that may index tonic attentional engagement during immersive VR rather than necessarily reflecting heightened anxiety, consistent with psychophysiological models of electrodermal activity (Boucein, 2012). By the same benchmarks, the SCL time effect was moderate-to-large (partial  $\eta^2 = 0.180$ ). Taken together with the SCR decrease, this pattern under VTL suggested concurrent sympathetic down-regulation of phasic arousal and sustained attentional activation during immersion.

Table 5  
Descriptive statistics and corrected RM-ANOVA results for SCR and SCL across phases

Index	Phase	Mean	SD	$F(GG \text{ corrected})$	$df(GG)$	$p$	Partial $\eta^2$
SCR	Pre	0.056	0.079	19.953	(1.361, 61.223)	< 0.001	0.307
	Mid	0.035	0.066				
	Post	0.023	0.046				
SCL	Pre	1.393	1.149	9.856	(1.088, 48.974)	0.002	0.180
	Mid	1.779	1.639				
	Post	1.985	1.996				

Note.  $F$  values and degrees of freedom are Greenhouse-Geisser corrected. Partial  $\eta^2$  indicates effect size (small = 0.01, medium = 0.06, large = 0.14). Significance threshold:  $p < 0.05$ .

Taken together, the psychological data revealed significant reductions in anxiety and improvements in vitality and affective balance, with relatively stronger effects observed for transient states such as state anxiety and negative affect. In contrast, the physiological data presented a more nuanced pattern: SCR showed a robust decrease, consistent with reduced phasic sympathetic arousal, whereas SCL showed a significant increase across phases. Rather than necessarily reflecting heightened anxiety, this increase may be interpreted as sustained tonic activation associated with attentional engagement during immersive tasks. The combined findings suggest that the VTL intervention may simultaneously attenuate anxiety-related arousal while maintaining physiological activation linked to immersion, indicating a multidimensional modulation of emotional and attentional processes.

## Discussion

This study, conducted in a sample of university students, explored the potential of VTL as a psychological intervention, revealing the crucial role of multi-sensory immersion, personalised experience and narrative and cultural depth as core elements of VTL design, along with their corresponding evaluation index system. Across end points, the largest improvements followed the immersive multi-sensory exposure,

supporting presence-driven sensory engagement as a primary lever for acute anxiety down-regulation. VTL, through high-fidelity sensory stimulation, induces a deep immersion experience, significantly reducing participants' immediate anxiety levels. This finding aligns with the core principles of ART (Kaplan & Kaplan, 1989) and the biophilia hypothesis (Wilson, 1986), which suggests that humans have an innate affinity with the natural environment; through "soft fascination", natural environments can reduce cognitive load and facilitate emotional regulation and psychological recovery (Basu et al., 2019; Pisalski et al., 2020). Multi-sensory stimulation alleviates cognitive fatigue and accelerates emotional recovery, by engaging involuntary attention, further supporting the positive impact of naturalistic environments on psychological regulation (Berto, 2014).

Beyond the significant reduction in state anxiety and changes in self-reported emotions, several underlying psychological and physiological mechanisms may contribute to VTL's effectiveness. The psychological processes involved may include attentional restoration, perceptual absorption and the engagement of prefrontal-limbic regulatory pathways. Immersive exposure to naturalistic environments is known to facilitate attentional decentering and may recruit prefrontal regulatory networks that modulate amygdala-driven reactivity – a neural mechanism commonly observed in cognitive emotion regulation paradigms (Ferri et al., 2016; Zhang et al., 2023). This modulation reflects deliberate, goal-directed emotional control, paralleling mechanisms observed in mindfulness and guided imagery interventions (Weder, 2022). Beyond these neural and psychological mechanisms, VTL's integration of visual, auditory and tactile multi-sensory inputs further enhances its therapeutic potential. High-fidelity dynamic visual landscapes, synchronised environmental sound effects and controlled tactile simulations, such as airflow and temperature regulation, collectively create an immersive sensory experience (Spano et al., 2023). It should be noted that, in the current implementation, tactile input was restricted to environmental parameters, while other modalities, such as olfactory stimulation or advanced tactile technologies, were not included. These omissions represent potential avenues for future research.

In terms of psychological outcomes, the present study demonstrated that VTL has a significant effect on state anxiety but a comparatively smaller impact on trait anxiety, which is more deeply rooted in enduring personality characteristics and long-term life experiences (Reeves et al., 2022). This finding suggests that, while VTL can acutely alleviate emotional distress, achieving sustained improvements in trait anxiety may require repeated exposures or extended interventions. Such long-term changes are likely to involve neuroplastic and neurochemical mechanisms, particularly within dopaminergic and serotonergic systems (Drigas & Sideraki, 2024).

Physiological data further support these psychological mechanisms. Specifically, SCR decreased significantly across experimental phases, indicating reduced phasic sympathetic activity and reflecting acute stress relief. This aligns with established theories and mechanisms of parasympathetic activation and autonomic rebalancing following restorative stimulation (Farahani et al., 2025; Lee et al., 2024). Conversely, SCL increased gradually, which, although directionally opposite, may indicate heightened sensory engagement or immersive attention rather than increased anxiety (Critchley, 2002). Such a dual pattern suggests that VTL evokes both physiological calming and cognitive engagement, supporting a multi-dimensional regulatory mechanism (Horvers et al., 2021).

The study also found that VTL's effect on alleviating negative emotions is notably stronger than its effect on enhancing positive emotions. This discrepancy may arise because the mechanisms for generating positive emotions are more complex and typically depend on external factors such as achievement, social support and interpersonal interaction (Fredrickson, 2001), which are not fully addressed in the current VTL design. This discrepancy may be attributable to asymmetries in the underlying neural pathways: While negative emotion suppression involves inhibition of limbic activity, the generation of positive affect may rely on dopaminergic reward networks and require stronger contextual stimuli (Kringelbach & Berridge, 2017).

In addition to sensory and emotional mechanisms, narrative and cultural depth represent significant extensions of the VTL design, playing an indispensable role in enhancing emotional regulation and

psychological intervention efficacy. The study found that the seamless integration of aesthetic art and contextual narrative endows the VTL content experience with deeper emotional value and cultural connotations, successfully triggering participants' emotional resonance and cognitive reflection. This result aligns with the environmental preference model's theoretical framework of complexity and mystery, highlighting the unique value of narrative and artistic elements in emotional regulation (Kaplan & Kaplan, 1989). The dynamic natural changes and landscape designs with cultural symbolism in the VTL experience not only significantly enhance participants' sense of immersion but also foster deep emotional connections and cognitive reflection. This finding is consistent with a previous study that emphasised the facilitative role of culture and art in psychological interventions (Takac et al., 2023). Furthermore, cultural differences in the acceptance of narrative and artistic elements suggest that there is room for optimisation in the cross-cultural applicability of VTL. By stimulating autobiographical memory and symbolic meaning, these narrative mechanisms may activate default mode network regions and enhance emotional regulation through internally directed cognition (Han & Northoff, 2008). To further enhance narrative engagement and meet diverse psychological needs, future research may also explore personalised scene customisation, facilitating long-term evaluation of its psychological effects.

## **Conclusion**

This study systematically explored the potential of VTL as an adjunct for alleviating anxiety and promoting psychological well-being among university students. The findings indicate that VTL may help reduce state anxiety, enhance subjective vitality, and improve emotional regulation, highlighting its potential as a pragmatic tool for mental health support in high-stress environments. On a theoretical level, this study supports an application of TL theory in VR contexts, offering insights into how multi-sensory experiences, streamlined interaction, and narrative elements may jointly support psychological restoration. The multi-dimensional design framework – encompassing sensory, interactive, personalised and content-driven experiences – offers design guidance for immersive therapeutic environments and clarifies how virtual settings can approximate the therapeutic effects of natural landscapes.

However, the study has certain limitations. First, it primarily focused on short-term intervention effects, and the long-term impact of VTL remains unexplored. The use of a short-term, single-scene VTL intervention was an intentional methodological decision to ensure high experimental control and internal validity. As an initial empirical attempt, this design allowed us to isolate and observe the immediate psychological effects of the overall VTL framework, particularly in reducing state anxiety, enhancing subjective vitality and regulating emotional responses. This approach ensured that findings were not confounded by scene variability, laying the foundation for more diverse and long-term applications. Building on this foundation, future studies should develop a broader range of VTL environments – such as coastal, forested and urban landscapes – and employ them in repeated or multi-week intervention cycles to systematically evaluate their cumulative effects on trait anxiety and other chronic psychological states.

Additionally, while the design emphasises high-fidelity visual and auditory experiences, other sensory modalities such as olfactory and tactile feedback were not fully explored, potentially limiting the overall immersion and therapeutic effect. Furthermore, while VTL effectively alleviates negative emotions, its impact on enhancing positive emotions is less pronounced. Future work should experimentally manipulate narrative pacing and affective salience to test whether such changes selectively increase PANAS-PA and modulate tonic EDA markers during exposure. In addition, adaptive parameter tuning could be coupled with brief physiological calibration to improve comfort and personalisation without increasing interaction burden. Moreover, given that most participants had limited prior VR experience, the potential influence of novelty effects cannot be fully ruled out. Future research should therefore involve populations with more diverse VR usage backgrounds and broader demographic characteristics, thereby enhancing causal attribution and external validity.

In conclusion, VTL demonstrates strong potential as a flexible adjunct to mental health interventions, particularly for alleviating anxiety and supporting emotional regulation. To fully realise this potential, future research should prioritise longitudinal trials, cross-cultural evaluations and systematic comparisons

with established interventions. Moreover, further refinement of multi-sensory integration, personalised adaptation and narrative resonance may enhance its therapeutic effectiveness. With these advancements, VTL could evolve into a scalable, versatile approach for psychological recovery, enriching mental health strategies across populations and settings.

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## Author contributions

**Yi-Tong Cui:** Conceptualisation, Methodology, Investigation, Writing – original draft, Writing – review & editing; **Wenwen Shi:** Visualisation, Supervision, Writing – review & editing; **Weicong Li:** Conceptualisation; **Boshen Hu:** Investigation, Data curation; **Yihong Liu:** Investigation, Data curation; Yun Qian: Project administration; **Haidong Xi:** Formal analysis, Data curation.

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