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Healing with sight, smell and sound: A virtual reality study on multisensory synergistic stress recovery in hospital staff break spaces

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HIGHLIGHTS

- Integrated VR, orthogonal design and psychophysiological metrics to assess recovery.
- Virtual break spaces constructed based on real healthcare staff preferences.
- Natural sensory combinations consistently yield the most effective stress relief.
- Multisensory synergy drives stress recovery via independent, additive effects.
- Vision leads physiological recovery while sound and smell drive subjective relief.

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ABSTRACT

Healthcare professionals endure chronic stress, yet current hospital break space design predominantly focuses on visual perception, often overlooking the synergistic potential of multisensory environments. This study investigates the stress-restorative effects of combined visual, auditory, and olfactory stimuli. Virtual environments were specifically constructed based on spatial element preferences derived from a survey of 180 healthcare professionals. Utilizing Virtual Reality (VR), an orthogonal experiment was conducted with 72 participants exposed to varying sensory conditions. Restorative outcomes were comprehensively assessed using psychological scales, including the Sensory Pleasantness Scale (SPS), the Positive and Negative Affect Schedule (PANAS), and the Perceived Restorativeness Scale (PRS), as well as physiological indicators, including electrodermal activity (EDA), heart rate variability (HRV), blood pressure (BP), pulse rate (PR), and blood oxygen saturation (SpO_2). The results demonstrate that natural sensory combinations consistently yielded the most effective stress relief. Crucially, variance analysis indicated that the sensory modalities exert robust, independent, and additive restorative effects. This cumulative synergy demonstrates that maximum restoration is achieved through an integrated multisensory approach. Furthermore, a distinct sensory hierarchy emerged: visual stimuli primarily established the physiological baseline for recovery, whereas auditory and olfactory cues overwhelmingly dominated subjective psychological restoration. The findings advocate for a paradigm shift in hospital design from mere "visible" considerations to a holistic "hearable and smellable" multisensory ecosystem, providing evidence-based strategies to mitigate occupational burnout.

1. Introduction

Hospitals are highly complex building types, yet the spatial needs of healthcare professionals are often eclipsed by clinical and patient-centered priorities, despite their prolonged exposure to high occupational stress. Negative emotional states are prevalent among healthcare professionals [72]. Hospital staff break spaces must therefore actively support stress recovery, especially in fully indoor rooms that offer better proximity to clinical workstations [7,47]. Compared to outdoor landscapes, these indoor environments often lack the necessary restorative qualities to effectively reduce stress and regenerate mental capacity [63,76]. Unlike typical workplace settings, hospital environments frequently underserve staff through inadequate respite areas. The combination of

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Nomenclature

OED Orthogonal experimental design
ANS Autonomous nervous system
SNS Sympathetic nervous system
PNS Parasympathetic nervous system
SPS Sensory pleasantness scale
PANAS Positive and negative affect schedule
PRS Perceived restorative scale
EDA Electrodermal activity
SCL Skin conductance level
SCR Skin conductance responses
SCL Rect50% Skin conductance level 50% recovery time
ECG Electrocardiogram
HRV Heart rate variability
LF/HF Ratio of low to high-frequency power
SDNN Standard deviation of the interbeat intervals of normal sinus beats
RMSSD Root mean square of successive differences between normal heartbeats
PR Pulse rate
SBP Systolic blood pressure
DBP Diastolic blood pressure
SpO_2 Blood oxygen saturation

spatial constraints, a lack of privacy from patients, minimal access to nature, and suboptimal olfactory and acoustic conditions severely limits the restorative value of these areas [83,117]. High-quality break areas are thus a functional necessity, with many healthcare professionals identifying them as essential for reducing health issues and enhancing job performance [85]. The Biophilia Hypothesis [51] posits an inherent human preference for nature, providing a fundamental evolutionary basis for why natural stimuli foster well-being. Building on this, Attention Restoration Theory (ART) [49] and Stress Recovery Theory (SRT) [104] further explain how natural visual, auditory, and olfactory elements facilitate cognitive and physiological recovery. Such restorative effects are commonly assessed through a combination of psychological scales and physiological indicators [16]. Simulation-based methods enable controlled, repeatable, and manipulable experimental conditions [44,98] and are widely applied in architectural and environmental research to support early-stage design decisions [55,79,84].

However, existing studies on restorative built environments, including hospital settings, remain predominantly vision-centered. Human spatial experience is inherently multisensory, involving vision, audition, olfaction, gustation, and touch [37,54,82]. In this study, we focus on vision, audition, and olfaction since gustation is less directly related to spatial perception, while touch is often contingent on material contact and tends to play a secondary role with lower sensitivity in routine workplace contexts [37]. Prior work has shown that these sensory modalities collectively affect stress perception and work efficiency [54]. In the specific context of hospital staff break areas, nature-based visual simulations offer significant restorative value [76], while controlled acoustic environments and quiet zones are critical for the auditory recovery of clinical staff [77]. These interactions can be synergistic [65], yet coordinated sensory investigations in indoor hospital settings remain scarce. Treating these modalities as independent may conceal important multisensory mechanisms relevant to staff restoration.

To address this gap, the present study aims to systematically examine the psychophysiological stress recovery effects of combined visual, auditory, and olfactory stimuli in hospital staff break spaces, and to answer the following core research questions: How do visual, auditory, and olfactory factors jointly influence healthcare professionals' stress recovery in indoor break space settings, and which sensory combinations maximize stress recovery outcomes? Do cross-modal synergistic effects exist and how do the senses interact and contribute to stress recovery? Utilizing Virtual Reality (VR), an orthogonal experiment

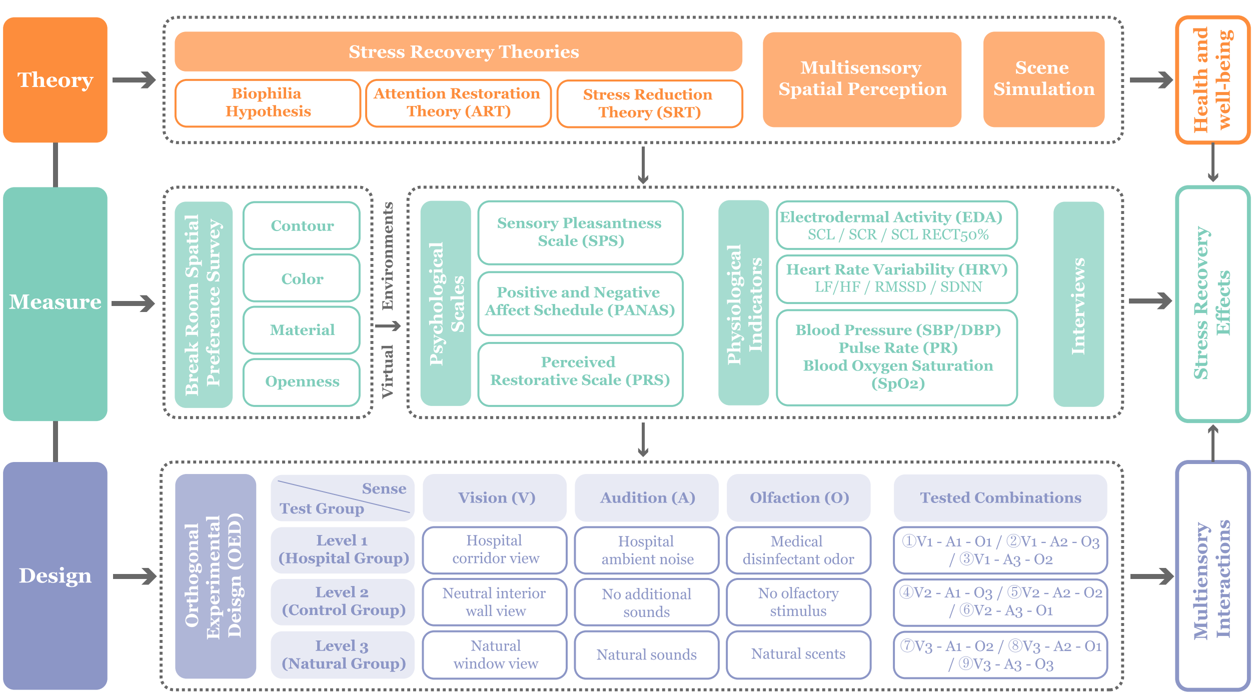

Fig. 1. Research framework.

was implemented to expose participants to varying sensory conditions. Restorative outcomes were assessed using psychological scales, including the Sensory Pleasantness Scale (SPS), Positive and Negative Affect Schedule (PANAS), and Perceived Restorativeness Scale (PRS), as well as physiological indicators, including electrodermal activity (EDA), heart rate variability (HRV), blood pressure (BP), pulse rate (PR), and blood oxygen saturation (SpO_2). The framework is shown in Fig. 1.

Focusing on multisensory interactions and sensory hierarchies, this study intends to clarify the patterns by which vision, audition, and olfaction jointly contribute to stress recovery, including their relative roles and interactive effects. By identifying sensory combinations that support more effective psychophysiological recovery, this study provides evidence-based guidance for multisensory design strategies in hospital staff break spaces and other restorative indoor hospital settings, thus helping enhance healthcare professionals' well-being in high-demand workplaces. In this context, the research aligns with the United Nations Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being) and SDG 11 (Sustainable Cities and Communities) [21].

2. Literature review

2.1. Theories and measurements of stress recovery

Stress recovery in built environments is grounded in environmental psychology, anchored by the Biophilia Hypothesis [51], which asserts an innate biological affinity for nature, encompassing the full human sensory apparatus. Building on the multisensory roots of the Biophilia Hypothesis, recent clinical and workplace studies demonstrate that multisensory natural stimuli, particularly the integration of olfactory and auditory cues from nature, yield superior restoration compared to isolated visual interventions [65,112,113]. These findings refine biophilic design principles [20] by emphasizing that holistic natural experiences are essential for optimal physiological recovery. This evolutionary process is further explained by Stress Recovery Theory (SRT) [104] and Attention Restoration Theory (ART) [49], and provides the framework for instruments such as the PRS to quantify environmental restorative potential.

Experimental assessment of stress primarily relies on the measurement of emotional responses. Being one of the most widely adopted theoretical frameworks, the valence-arousal two-dimensional model of emotion proposes that core emotions exist as continuous states in the brain and are defined along two dimensions: valence and arousal. Valence ranges from pleasant to unpleasant and represents the degree of emotional positivity, while arousal ranges from activation to deactivation and reflects the intensity of emotional experience [14].

Methods for measuring emotion generally fall into two categories. The first consists of subjective assessments, such as questionnaires and self-report scales (e.g., the PANAS scale [108]). The second category involves objective physiological measurements, which assess emotion by capturing signals from physiological systems that link the central and peripheral nervous systems. Emotional and stress responses are closely linked to activity in the autonomic nervous system (ANS), including the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS), which govern unconscious, automatic bodily regulation. The SNS is more active under stress, while the PNS supports rest and recovery. Experimental methodologies for assessing the health impacts of indoor architectural materials on psychological stress have been summarized across five major physiological systems, and the most frequently employed indicators include EDA, HRV, BP, and SpO_2 [74]. Cardiovascular measures such as HR and BP, as well as skin-related measures including EDA, are primarily influenced by sympathetic activity, whereas peripheral oxygen saturation (SpO_2) is typically monitored as a basic oxygenation and safety index in both laboratory and VR-based intervention studies [25,107]. HRV is predominantly modulated by parasympathetic activity.

2.2. Multisensory spatial perception

Multisensory spatial perception is theoretically grounded in Gestalt Perceptual Theory and Embodied Cognition Theory, both of which emphasize that human experience of space arises from the integrated processing of multiple sensory inputs rather than from isolated sensory channels. Gestalt Perceptual Theory argues that perception is inherently holistic: sensory information is organized and structured by the nervous system into coherent wholes, enabling individuals to efficiently interpret complex environmental stimuli, forming the basis of holistic environmental cognition [28]. Complementarily, Embodied Cognition Theory conceptualizes perception as part of a continuous sensory - perceptual - cognitive - action loop, in which environmental stimuli influence subjective cognition, emotion, and behavior through multiple sensory pathways at both conscious and subconscious levels [24]. The collection and reconstruction of sensory data in the brain thus constitute a fundamental mechanism underlying multisensory cognition [88].

Despite this theoretical foundation, traditional architectural and built environment research has prioritized visual form and performance, leaving limited scope for systematic engagement with auditory, olfactory, and tactile modalities [109]. Although recent decades have witnessed increasing interest in incorporating non-visual sensory modalities, giving rise to the field of Multisensory Design (MSD) [69], empirical research remains uneven across the senses. Most existing studies continue to focus on visual variables such as lighting, color, and spatial openness in relation to stress recovery [83], while auditory [48,99] and olfactory influences on the living environment [22,38,62,97] have received comparatively limited attention. This imbalance persists despite substantial evidence demonstrating the restorative effects of natural soundscapes [5,110] and the significant role of olfaction in shaping emotion, behavior, stress, and cognitive performance [4].

Emerging studies that integrate multiple sensory modalities underscore the importance of cross-modal interactions. Research combining visual and auditory stimuli has shown that multisensory exposure can enhance stress recovery and health outcomes compared with unimodal visual conditions [45,110,115]. Similarly, studies examining auditory-olfactory combinations reveal reciprocal relationships between sensory channels, whereby positive stimulation in one modality can enhance perceptual sensitivity in another, and vice versa [4,5]. By contrast, investigations integrating visual and olfactory modalities remain relatively limited, with only a small number of studies employing physiological indicators to examine their combined restorative effects [97].

Crucially, research addressing the integrated and interactive effects of three or more sensory modalities remains scarce. Although some studies have incorporated visual, auditory, and olfactory variables, these modalities are often treated as parallel or additive components rather than as dynamically interacting systems [36,87,94,96]. As a result, the holistic mechanisms through which multisensory environments shape stress perception, emotional regulation, and cognitive appraisal remain insufficiently understood. Taken together, existing theories and empirical findings suggest that multisensory spatial perception cannot be adequately explained through single modality or simple combinatorial approaches. Instead, there is a clear need for systematic investigations that conceptualize sensory modalities as an interacting whole, particularly in stress restorative spaces where multisensory integration is likely to play a decisive role.

2.3. Virtual reality scene simulation

VR has emerged as one of the most widely used and effective tools for spatial scene simulation and perceptual experimentation. Compared with on-site experiments, full-scale constructed rooms, 1:1 physical mock-ups [32,53], and two-dimensional media such as images [31,105], VR provides a cost-efficient platform for comparing complex spatial conditions. VR-based simulation is decoupled from the physical world [100]. Following the principle of Behavioural Realism, its high visual fidelity elicits psychophysiological responses and emotional arousal comparable to real-world experiences [31,78]. These advantages have led to its widespread use in studies of restorative environments and landscapes [1,36,66].

Recent reviews further note that VR is not only a visualization tool, but also an experimental platform for representing combinations of biophilic patterns, providing multimodal sensory inputs, supporting stress-induction tasks, controlling exposure duration, and measuring human biological responses to natural environments [73]. In biophilic and restorative research, immersive virtual environments are increasingly used to investigate environmental perception, physiological and psychological indicators, and cognitive outcomes, while enabling the controlled manipulation of visual, acoustic, and other sensory variables [17]. Despite fragmented evidence, immersive VR offers a flexible and rigorous way to construct and compare biophilic settings involving multiple sensory domains.

Another methodological advantage of VR is its compatibility with wearable physiological monitoring tools, allowing users' objective responses to be captured during controlled environmental exposure. This approach has been used in immersive studies of stress or anxiety recovery, and in user-centered evaluations of thermal perception and physiological state, using indicators such as HRV, HR, SCL and BP [90, 114]. Recent reviews also confirm the growing integration of wearable biosensors into immersive VR research [33]. Together, these features provide a solid methodological basis for the present study.

2.4. Restorative perception in hospital environments

In recent years, human-centered healthcare environments have gained growing attention. An increasing body of research has examined overall hospital environments or specific spatial types, focusing on their design rationality and restorative potential for users' psychological well-being.

In multisensory hospital-environment research, most studies have concentrated on outdoor therapeutic settings, such as healing gardens and landscaped hospital exteriors, and their restorative potential [11,19,65]. The literature remains largely patient-centered, with fewer investigations addressing healthcare staff [50], and even fewer focusing specifically on staff break spaces. Previous research on hospital staff break spaces has identified key restorative factors but has consistently overlooked the synergistic potential of multisensory integration. Early work by Nejati [75] used interviews to define functional amenities, providing a foundational but subjective understanding of staff needs. While subsequent findings confirmed the restorative benefits of balconies and windows, they remained limited to qualitative self-reports [117]. Even in studies using visual simulations, the investigation has remained confined to unimodal stimuli, highlighting a critical gap in understanding the holistic, multisensory nature of staff respite environments [76]. Therefore, research addressing restorative perceptions in hospital environments remains insufficiently focused on healthcare staff, and multisensory effects have rarely received attention or been translated into concrete renovation or design strategies.

3. Methodology

3.1. Experimental design

3.1.1. Environment set-ups

The experiment was conducted in December 2025 at the School of Architecture, Tsinghua University. All experimental sessions were scheduled between 9:00 AM and 6:00 PM. Throughout the experiment, the room environment was kept silent and odorless, with stable and comfortable thermal conditions (mean temperature: 23 °C; mean relative humidity: 48%). The room was equipped with a fresh-air ventilation system capable of rapidly removing residual odors generated during the experiment. The experimental set-ups are illustrated in Fig. 2.

The virtual architectural space, depicting a prototype staff break space, was delivered as immersive VR videos (4096 × 2048 pixels, 100 fps) and viewed through a PICO 4 Enterprise headset, which features dual 2.56-inch diagonal displays, with a per-eye resolution of 2160 × 2160 pixels, a maximum refresh rate of 90 Hz, and a field of view of approximately 105°. All VR video content was preloaded into the internal storage of the headset and played locally on the device to avoid latency and frame-rate fluctuations. Auditory stimuli were delivered via in-ear active noise-canceling earphones (AirPods Pro 3). Olfactory stimuli were provided using 0.4 mm cotton scent strips soaked with odorants and mounted on a holder positioned directly beneath the participant's nose. Physiological signals were collected using multiple devices: EDA and HRV were recorded with a PhysioLab sensor; SpO_2 was measured using a KS-CM01 smart pulse oximeter; BP and PR were recorded with an Omron upper-arm blood pressure monitor. BP data were manually recorded after each measurement (after exposure to the blank scene and one of the two experimental scenes), while all other signals were transmitted in real time to their respective monitoring platforms and subsequently exported for analysis. The experimental design is shown in Fig. 3.

3.1.2. Constructing virtual break spaces: a survey of preferred spatial factors

Given the significant variation in staff break spaces across different healthcare facilities, it is necessary to preliminarily determine spatial forms based on the preferences of healthcare professionals before constructing virtual environments aimed at measuring multisensory stress relief. Due to the multitude of spatial variables and their combinations, it is impractical for participants to experience or evaluate each one individually. Therefore, this study employs a survey-based image ranking method to conduct a selection of break space preferences, providing a basis for the subsequent construction of the virtual environments. Utilizing 2D images for the rapid, batch preliminary screening of spatial factor preferences prior to conducting detailed experiments is a widely recognized and effective method [66,76]. Crucially, employing a preference survey for this initial screening serves a fundamental purpose: it prevents the experimenters' subjective design biases from dictating the spatial forms. This ensures that the simulated environments remain highly representative of authentic healthcare staff preferences and are tightly grounded in real-world clinical realities.

This study selected and extracted important high-level spatial variables frequently addressed in previous studies, primarily covering spatial layout [80], contour [32], color [56,68], and material [53]. Specifically, layout is categorized into public and private based on openness; contour is divided into angular and curved types, including aspects such as spatial shape [106] and furniture form; color is primarily classified by color temperature into cool, warm, and neutral tones; and material divides the enclosing wall surfaces into paint, wallpaper, and wood. Due to the specific constraints of medical spaces, common variables that are restricted (e.g., ceiling height) and other lower-level variables that do not affect the intrinsic nature of the space, such as decorations and signage, are not considered at this stage.

Based on real-world usage scenarios in hospitals, this study constructs three representative types of staff break spaces: enclosed spaces in treatment areas (small-scale spaces), open spaces in treatment areas (corridor/circulation spaces), and centralized spaces in staff areas (large-scale spaces). The variables were combined within each of the three space types to generate distinct spatial scenes. In this study, the multi-factor analysis of spatial elements generated a complex number of combinations. A full factorial design would require an excessively large number of trials (36 combinations per space type), which is practically impossible to implement due to high time, labor, and material costs. Therefore, this study employs OED, which is a highly efficient method based on orthogonal arrays [65,116]. OED selects representative points that are distributed uniformly within the test range, thus representing the overall situation without testing every single combination [116].

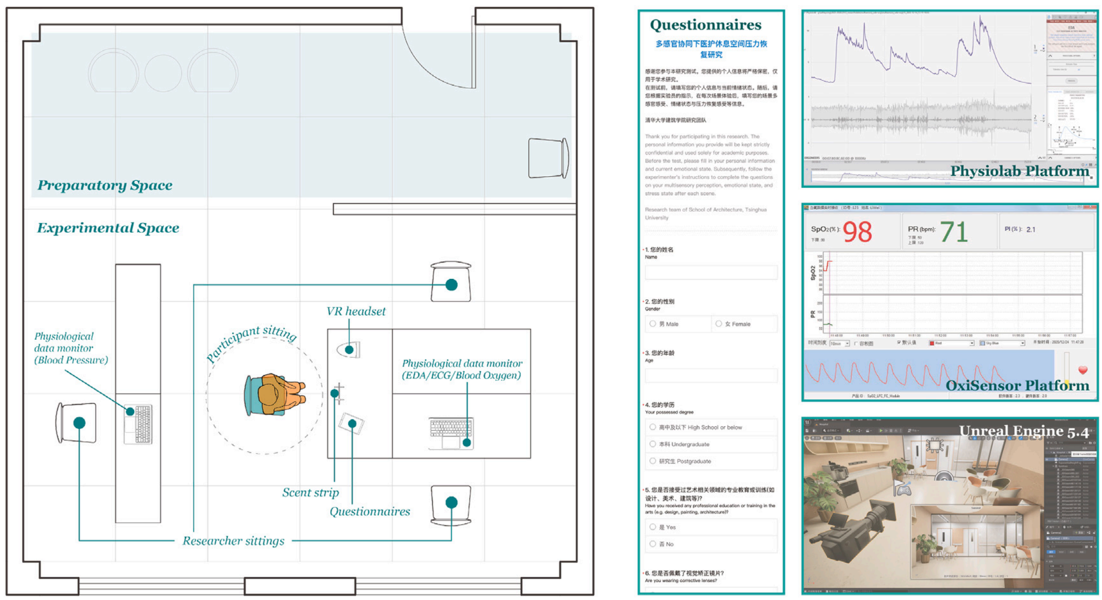

Fig. 2. Experimental set-ups: room layout, questionnaires and software.

This approach further reduces the ranking burden on participants without compromising the validity of the conclusions. Additionally, OED helps control for potential confounding factors and minimizes experimental error [65]. Ultimately, by applying a standard mixed-level L_{18} orthogonal array, 18 representative spatial combinations were systematically selected from the 36 possible combinations for each space type, totaling 54 combinations. These were modeled using Rhinoceros 8 and rendered with Enscape (v3.4.4). Each space type was designed as a break room unit prototype with a standard rectangular aspect ratio of 3:2 and a spatial module of 6 m × 4 m, incorporating necessary elements such as food preparation areas, storage spaces, and sinks.

The survey utilized the MaxDiff format to determine preference rankings through comparison; in each set of randomly presented spatial combinations, participants were asked to select their most and least preferred scenes. In accordance with the minimum sample size requirements for MaxDiff [81], the study recruited 180 frontline healthcare professionals from general hospitals across multiple provinces in China. The age distribution was roughly balanced (aged 20–59 years), and occupational types were distributed to reflect the actual user population of staff break spaces: doctors and nurses each accounted for approximately 40%, while medical students working in hospitals and administrative staff each accounted for approximately 10%. Demographic details are summarized in Appendix Table A.

Following the survey, the study further conducted interviews with 108 of the participating healthcare professionals to inquire about their visual, auditory, and olfactory sensory evaluations of the break spaces currently utilized in their work, as well as their suggestions for improvement. The conclusions of the survey and the interviews are presented in Section 4.1 and serve directly as the basis for the construction of the virtual environments in the formal experiment.

3.1.3. Virtual environment

This study employed OED to combine and screen multisensory stimulus conditions. Three sensory independent variables were defined: visual, auditory, and olfactory stimuli. Each sensory category comprised three corresponding conditions: Level 1 (Hospital), Level 2 (Control), and Level 3 (Nature), as shown in Fig. 1. As mentioned in the previous section, a full factorial design for these three factors with three levels each (3 × 3 × 3) would require 27 distinct experimental groups. Repeating each group adequately to meet statistical requirements would result in an unmanageable workload and potential participant fatigue [65]. Therefore, OED was utilized to efficiently and economically sample representative points. To ensure no unintentional subjective bias was introduced during the selection of these combinations, we strictly applied a standard $L_9(3^3)$ orthogonal array. This mathematical array strictly guarantees that the data points are distributed evenly and orthogonally [116], meaning every level of a factor is paired exactly once with every level of the other factors. Following this rigorous rationale, nine exact representative multisensory combinations were derived for the formal experiment. The complete multisensory tested combinations are comprehensively listed in Table 1.

For the visual stimuli, the virtual architectural space was modeled in Blender (v5.0.1, 2025). While our preliminary survey evaluated three typical break spaces (enclosed, corridor, and centralized), yielding comprehensive baseline data for multi-scale hospital design as an independent contribution, only the enclosed space was selected as the VR prototype. This decision was driven by three primary considerations: First, according to the survey results, the enclosed type exhibited the largest overall variance in preference shares across the four design dimensions, making its preferred features the most prominent and distinct. Second, to strictly control the core visual, auditory, and olfactory variables in the VR experiment and prevent confounding effects, a highly representative and standardized spatial prototype was required. As the smallest and most ubiquitous form of break space in typical hospital environments, the enclosed room serves as the optimal baseline. Third, these enclosed spaces are frequently adjacent to high-stress work areas, have limited floor areas, and often lack access to natural light. Consequently, healthcare professionals in these specific spaces face the most urgent practical need for multisensory synergistic interventions to facilitate stress relief. Based directly on the subjective preference results detailed in Section 4.1, this typical enclosed staff break space was characterized by a curved contour, warm color, painted wall surface, and private layout. The virtual environments were rendered using Unreal Engine (v5.4.4, 2025), since a high level of realism is critical for experiments simulating real-world environments [64,91]. Participants' viewpoints were positioned within a virtual staff break space measuring 9 m × 6 m × 3 m, facing either a blank wall (Control group) or a 6 m × 2.75 m floor-to-ceiling transparent glass window (Hospital and Nature groups). Participants were seated on a single sofa in the resting area, approximately 7 m from the window, with an eye height of approximately 1.1 m.

Fig. 3. Experimental design: a schematic diagram of the virtual environment and different sensory groups.

For the auditory stimuli, the Hospital group soundscape consisted of typical background noises of treatment areas, including conversations, footsteps, public address announcements, equipment movement, and HVAC system operation. The Nature group soundscape included common courtyard sounds, such as birdsong, flowing water, and wind through foliage. All audio materials were sourced from publicly available, high-quality sound libraries. Sounds with strong regional specificity or highly salient, abrupt events were excluded to improve generalizability and comparability. To minimize the influence of sound intensity, all auditory stimuli were loudness-normalized before playback, and presented within a comfortable range, at 50 dB for the hospital stimuli and 40 dB for the nature stimuli. In the blank control group, no additional auditory stimuli were introduced, only ambient background noise in the experimental environment was retained.

For the olfactory stimuli, the hospital odor stimuli employed a disinfectant solution with hypochlorous acid as the primary active component, with an available chlorine concentration of 100 mg/L (±15 mg/L). This served as a typical and contextually recognizable disinfectant cue in hospital environments. The natural odor stimuli used a liquid fragrance with plant sap and floral notes, including violet aldehyde, leaf alcohol (cis-3-hexen-1-ol), and related ester derivatives, with an overall scent profile dominated by grass, violet leaf, bergamot and woody notes. This stimulus was intended to simulate the natural odor characteristics of mixed plant-derived volatile organic compounds in

Table 1
Orthogonal experimental design of multisensory combinations.

Test combination	Vision (V)	Audition (A)	Olfaction (O)
1	Level 1 (Hospital)	Level 1 (Hospital)	Level 1 (Hospital)
2	Level 1 (Hospital)	Level 2 (Control)	Level 3 (Nature)
3	Level 1 (Hospital)	Level 3 (Nature)	Level 2 (Control)
4	Level 2 (Control)	Level 1 (Hospital)	Level 3 (Nature)
5	Level 2 (Control)	Level 2 (Control)	Level 2 (Control)
6	Level 2 (Control)	Level 3 (Nature)	Level 1 (Hospital)
7	Level 3 (Nature)	Level 1 (Hospital)	Level 2 (Control)
8	Level 3 (Nature)	Level 2 (Control)	Level 1 (Hospital)
9	Level 3 (Nature)	Level 3 (Nature)	Level 3 (Nature)

vegetated environments. All olfactory stimuli were delivered using scent strips, with a standardized loading amount of 2 mL per strip. The strips were positioned approximately 5 cm beneath the participants' noses, allowing passive evaporation during exposure. After each presentation, the scent strip was replaced and the room was ventilated by opening the window to reduce residual odor and carryover between stimuli. Although this method provides less control over absolute odor concentration and dispersion than an olfactometer or active scent-delivery system, it offered a simple, low-cost, and quiet form of odor presentation, without introducing additional device noise or airflow disturbance, and could be readily synchronized with the VR setup and physiological recording. Similar passive near-nose delivery approaches using paper or strip-based carriers have also been reported in studies of fatigue-related olfactory intervention and multisensory experience [42,46]. In the blank control group, no additional odor stimuli were applied.

3.1.4. Participants

Participants were recruited online, including students and staff from Tsinghua University and adjacent universities in Beijing. As the present study aimed to examine short-term restorative responses to a controlled multisensory environment, a non-clinical sample was recruited for the formal experiment. Similar staged designs have been adopted in prior studies, in which context-specific healthcare or restorative environments were first evaluated in simulated patients, healthy volunteers, or university samples before further validation in the intended population [57,101,107]. Eligibility was assessed using a screening questionnaire. Participants were required to be in good physical and mental condition on the test day, without acute sleep deprivation and no caffeine or alcohol intake prior to participation [29]. Individuals reporting pronounced susceptibility to simulator sickness or discomfort in immersive environments (e.g., severe dizziness, nausea, or claustrophobia) were excluded [8,41,93]. Participants were also required to have no sensory limitations that could interfere with the perception of experimental stimuli; all enrolled participants reported normal or corrected-to-normal vision. An a priori power analysis for a repeated-measures ANOVA was conducted using G*Power 3.1 [26,27]. The following parameters were entered: effect size $f = 0.25$, $\alpha = 0.05$, power $= 0.95$, number of measurements $= 2$, within-subject correlation $\rho = 0.5$. This indicated a minimum requirement of 62 participants. The final valid sample comprised 72 participants (30 males, 41.67%; 42 females, 58.33%; aged 18–39 years). As each participant evaluated two conditions, this yielded 144 observations. The independent participant sample ($N = 72$) exceeded the requirement, ensuring robust statistical power. Additional demographic characteristics are summarized in Appendix Table B.

Table 2
Summary of measurement indicators and methods.

Domain	Measurement indicator	Stress-recovery sign	Measurement method
Emotional arousal	EDA	↓ SCL, ↓ SCR	Physiolab (wearable)
	BP	↓ SBP (slight) ↓ DBP (slight)	Omron 10 (upper-arm BP monitor)
	PR	↓	
	SpO_2	↑ (slight)	KS-CM01 (smart pulse oximeter)
Emotional valence	HRV	↑ RMSSD; ↑ SDNN ↓ LF/HF	Physiolab (wearable)
Cognitive psychology	Subjective perceptual evaluation	↑ total score	SPS
Affective psychology	Subjective emotional evaluation	↑ total score	PANAS; PRS

3.2. Measurements

The experimental results included two components: subjective psychological indicators and objective physiological indicators. The measurement methods and expected signs of stress recovery are summarized in Table 2.

3.2.1. Psychological measurements

The selection of psychological scales considered both effectiveness and completion time. Three psychological scales were used, as shown in Fig. 4.

SPS assesses participants' sensory perceptions of the scenes across visual, auditory, and olfactory stimulation, including preference and pleasantness [67]. Each sensory modality is evaluated with multiple bipolar adjective pairs, allowing for a nuanced assessment of multisensory perceptual quality. PANAS is a widely used instrument to measure positive and negative affect. The short version adopted here [103] consists of five positive and five negative items. PRS measures perceived restorative effects across four dimensions: being away, fascination, coherence, and compatibility. Four items were selected for each dimension, yielding 16 items in total. All scales used a 7-point Likert scale, except PANAS, which followed its customary 5-point format. Before formal analysis, reliability was assessed with Cronbach's alpha (0.759) and validity with the KMO test (0.759).

3.2.2. Physiological measurements

This study selected a multidimensional set of physiological measures, including electrodermal activity (EDA), heart rate variability (HRV), pulse rate (PR), blood pressure (BP), and blood oxygen saturation (SpO_2), to capture rapid nervous-system and cardiophysiological responses during stress and recovery. Following common psychophysiological distinctions, EDA, BP, and PR were treated primarily as arousal-related indicators, while HRV was used to characterize autonomic balance and recovery-related variations.

For EDA, signals were decomposed into skin conductance responses (SCR) and skin conductance level (SCL) [61], and three indicators were extracted for analysis: SCL decrease, SCR, and the 50% recovery time of SCL (SCL Rect50%) [39,43,58,65,102]. For HRV, three commonly used parameters were selected: the standard deviation of normal-to-normal intervals (SDNN), the root mean square of successive differences (RMSSD), and the low-/high-frequency power ratio (LF/HF) [71,92]. PR was included as an additional cardiovascular indicator of physiological

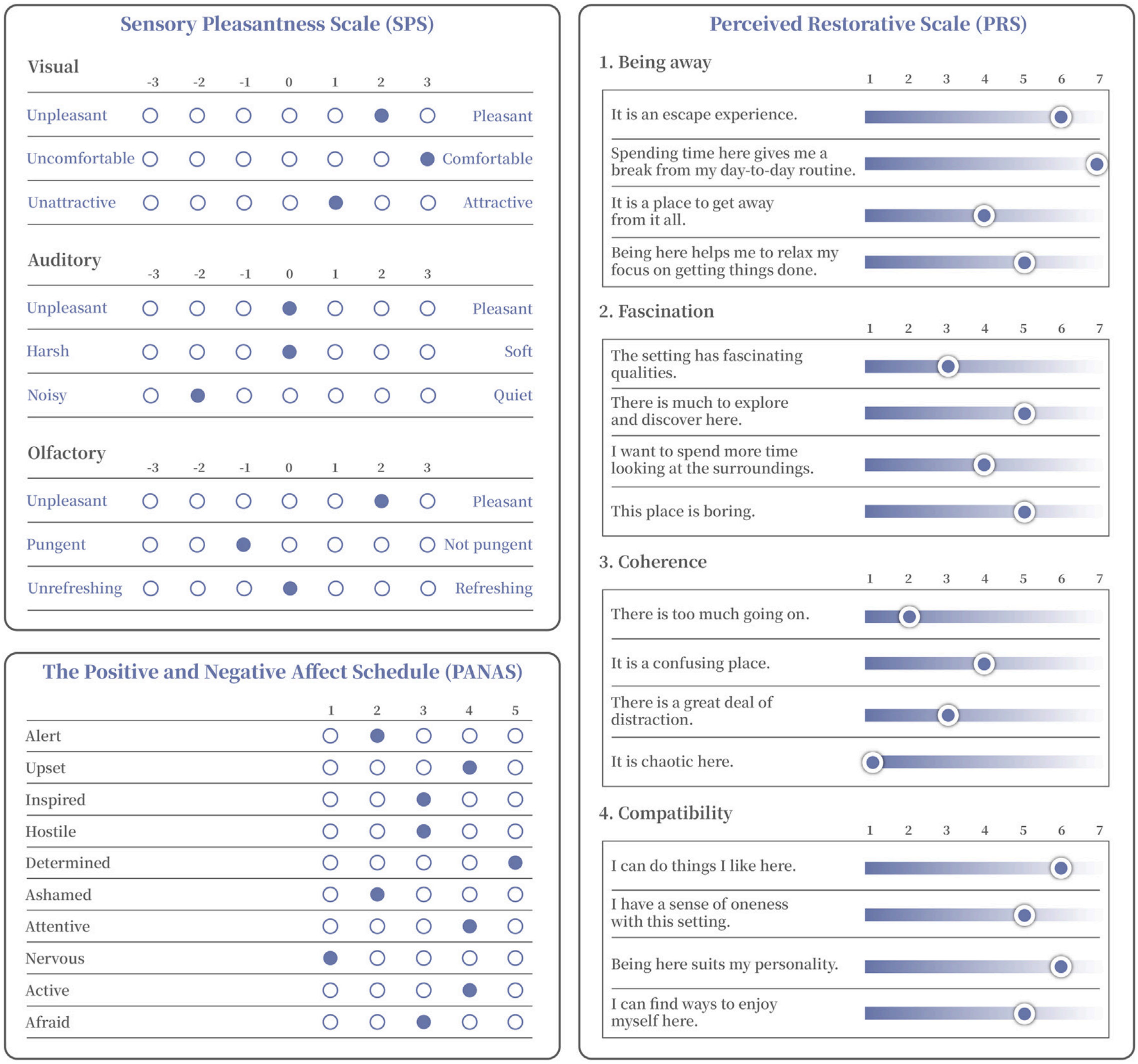

Fig. 4. The items in the psychological scales (SPS, PANAS, PRS).

arousal [12,60,111], while BP was represented by systolic blood pressure (SBP) and diastolic blood pressure (DBP), both commonly used to reflect acute physiological stress and recovery [35,114].

SpO_2 can indicate stress states through respiratory efficiency. In healthy adults, peripheral oxygen saturation is tightly regulated and typically remains within the normal range ($\approx 96-99\%$), with only minimal variation under mild psychological stress [23,34]. Accordingly, in this study, it served as a stable reference measure to verify that the VR exposure and multisensory manipulations did not compromise cardiopulmonary stability [25].

3.3. Experimental procedure

The experiment lasted approximately 30 minutes and comprised seven phases, as shown in Fig. 5. The four consecutive phases spanning from the stress phase to the end of the subsequent break phase constituted one complete session; each participant completed two sessions to evaluate two multisensory conditions. To explicitly rule out the potential influence of order and learning effects, the exposure sequence of the two multisensory conditions was strictly randomized for each participant. Furthermore, to mitigate sensory adaptation and carryover effects, a mutually exclusive sampling strategy was implemented: the two combinations assigned to each participant were constrained to have completely non-overlapping levels across all three sensory dimensions. The protocol was reviewed and approved by the Tsinghua University Ethics Committee.

During the preparation phase, participants received study instructions and provided written informed consent. They then completed a demographic questionnaire and items assessing visual acuity, such as the use of corrective lenses. Participants were subsequently fitted with physiological sensors. After completing a baseline PANAS assessment, they were instructed to remain still, minimize conversation, and put on the VR headset and headphones. The synchronous recording of physiological signals then began, followed by approximately 3 minutes of exposure to a neutral control VR scene to stabilize emotional and physiological states.

Before experiencing the experimental scenes, the participants completed stress-inducing tasks designed to rapidly elicit negative psychophysiological responses, thus creating contrast relative to baseline levels. The tasks comprised two time-limited sections: a numerical reasoning task and a backward digit-span task, both of which are commonly used for stress induction [18,40,59,102].

Next, participants re-entered the VR environment and underwent a 2-min multisensory scene exposure under the assigned condition, during which physiological signals were continuously recorded. Immediately after exposure, participants completed the SPS, PANAS, and PRS questionnaires. A brief break period then followed until physiological

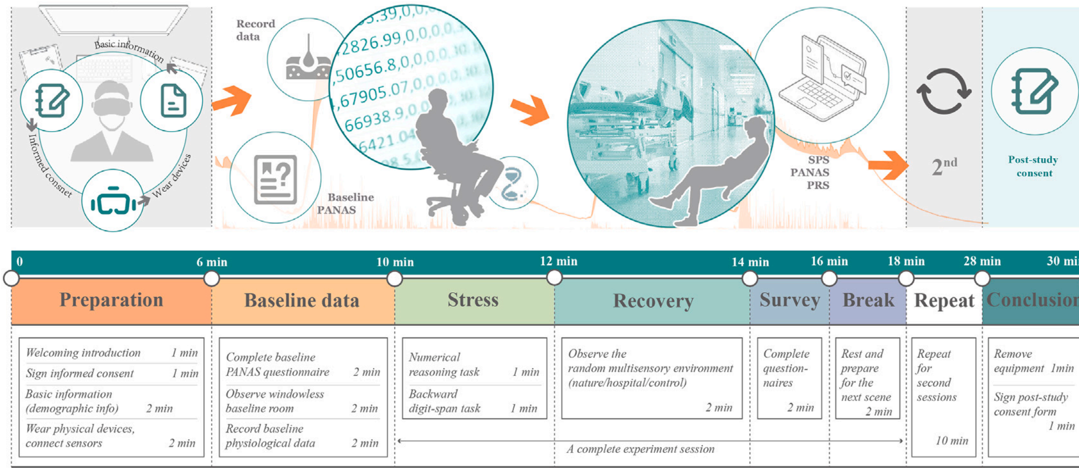

Fig. 5. Experimental procedure.

measures returned to baseline, after which the stress-recovery sequence was repeated under the second condition.

At the end of the experiment, participants signed a post-study consent form and participated in a brief interview focusing on their experiences, perceptions, and subjective responses to the multisensory conditions, including how different senses were perceived during the recovery process.

3.4. Data analysis

3.4.1. Physiological data preprocessing

EDA and ECG data were sampled at 1000 Hz in this experiment. Given that EDA signals are characterized by low-frequency components, the sampling rate was first downsampled to 10 Hz for subsequent analysis. Raw EDA data were acquired in digital form and then converted into analog values expressed in microsiemens (μS) to facilitate further processing [9]. The converted data were imported into IBM SPSS (v26.0) for initial screening, during which extreme values were identified and removed. Subsequently, EDA data were analyzed using the Ledalab toolbox (v3.4.9) in MATLAB (R2024b). Through Continuous Decomposition Analysis, the EDA signals were decomposed into two components: SCL and SCR.

The raw ECG data were preprocessed and feature-extracted in a Python 3.11 environment using the NeuroKit2 package. First, band-pass filtering and artifact correction were applied to the raw ECG signals to reduce the influence of baseline drift and high-frequency noise on R-peak detection. After obtaining cleaned R-R interval sequences, multiple HRV indices such as SDNN and RMSSD in the time domain, LF and HF in the frequency domain were computed, and LF/HF was subsequently calculated.

All indices were computed within time frames defined by experimental event markers. Based on the recorded timestamps, for each participant, the first minute of stable signal during the stress task phase and the subsequent recovery scene were extracted for analysis. The mean values obtained during the stress task phase were used as individual baselines, and all recovery phase indices were normalized according to the following formula [3]:

$$\%\Delta x = (x - x_{\text{baseline}})/x_{\text{baseline}} \times 100\% \tag{1}$$

3.4.2. Statistical analysis

Data analysis, including examinations of data distribution, variance, simple effects, and correlations, was primarily conducted using Python and SPSS. Psychological data were analyzed using raw questionnaire scores. Given the individual variability in physiological data, a normalization procedure was applied prior to analysis according to formula (1) to eliminate the influence of individual baseline differences. For analyses involving physiological data, z-score standardization was performed. Z-scores were obtained by subtracting the sample mean from the individual value and dividing the result by the standard deviation [10].

Because each participant evaluated two mutually exclusive conditions, the resulting observational data were not strictly independent. To appropriately handle this repeated-measures structure within the fractional $L_9(3^3)$ orthogonal array, a Mixed-effects Analysis of Variance (Mixed ANOVA) framework was employed. In these models, the sensory factors were entered as fixed effects to examine the differing characteristics across their respective levels, while Participant ID was designated as a random effect to strictly account for intra-subject correlations and individual baseline variations. Assumptions of normality for the model residuals were evaluated using the Shapiro-Wilk test. For post-hoc pairwise comparisons between specific factor levels, Estimated Marginal Means (EMMs) were utilized. To strictly control the family-wise experimental error rate during these multiple comparisons, the Bonferroni correction was applied [30]. In this paper, * indicates significant ($p < 0.05$); ** indicates very significant ($p < 0.01$); *** indicates highly significant ($p < 0.001$); n.s. indicates not significant.

Regarding effect sizes, partial eta-squared (η_p^2) was adopted as the primary indicator to evaluate the magnitude of the main and interaction effects within the ANOVA framework. Thresholds of 0.01, 0.06, and 0.14 were used to interpret the effect sizes as "small", "moderate", and "large", respectively [15]. For specific pairwise comparisons, Cohen's d was reported. Furthermore, given the potential interactions among the three factors in this study, simple effects analysis was employed to further investigate the nature and types of two-way and three-way interactions. Concurrently, Pearson's r was used to analyze correlations between indicators. Finally, visualizations were generated using Jupyter Notebook.

4. Results

4.1. Preference for spatial factors of staff break spaces

The study utilized preference share as the statistical metric, defined as the proportion of times a specific attribute was selected as "most preferred" (or "least preferred") relative to the total number of attribute selections. A Chi-square goodness-of-fit test was conducted on the data, and the results indicated that preferences for all spatial elements across the three space types exhibited highly significant differences ($p < 0.001$) (Appendix Table C).

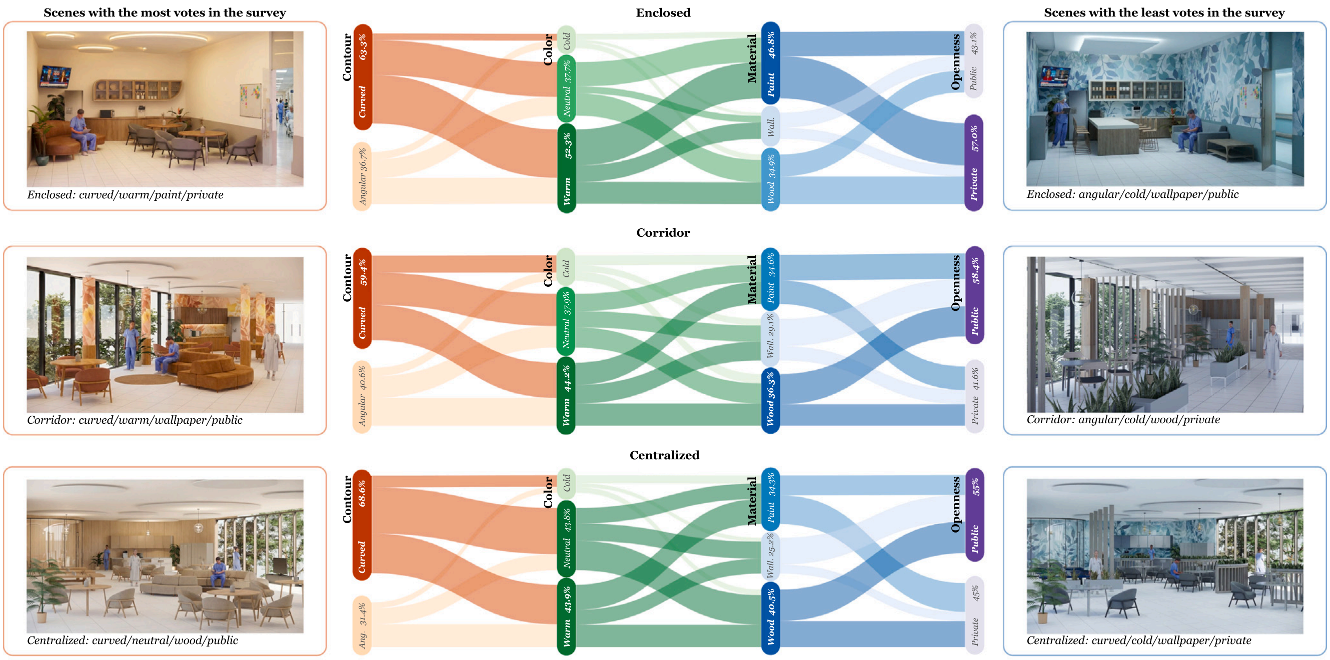

Fig. 6. Preference shares for spatial factors of different break space types. Scenes with the most and least votes in the survey are respectively shown on left and right.

Fig. 6 displays the preference shares for the decomposed spatial elements within each space type. The results across the enclosed, corridor, and centralized spaces demonstrate a unified preference for curved forms and neutral-to-warm colors, alongside distinct local variations. Notably, material preferences correlate with space size: simple materials (e.g., paint) are preferred in smaller spaces, whereas textured materials (e.g., wood or patterned wallpaper) are favored in larger ones. Similarly, openness preferences depend on spatial location, with participants prioritizing privacy in smaller rooms and publicness in larger or corridor areas.

These survey results directly dictated the virtual environment construction, avoiding the subjectivity typically associated with VR modeling. By strictly adopting the most preferred elements for the enclosed space (“curved / warm / paint / private”), the design integrated both specific local preferences and cross-spatial aesthetic commonalities. This evidence-based selection ensured the simulated environment possessed high ecological validity and broad applicability for the subsequent formal experiment.

4.2. Psychological data analysis

Fig. 7 displays the results of the SPS, PANAS, and PRS scales, with the x-axis representing the rating scores for each dimension. From left to right, the three scales sequentially illustrate the scores for vision, audition, and olfaction. In each graph, the three line plots represent the three levels of a specific sensory type.

Table 3 reports the results of the Mixed ANOVA for the three psychological scales, including the degrees of freedom (df_1, df_2), test statistics (F), Bonferroni-corrected significance (p-value), and effect size (η_p^2). Consequently, post-hoc pairwise comparisons based on EMMs were conducted to identify specific between-group differences. The mean differences (ΔEMM), standard errors (SE), test statistics (t), Bonferroni-corrected significance (p-value), and effect size (Cohen’s d) for each comparison are also provided for reference (Appendix Table D).

4.2.1. SPS

The results of the SPS scale reflect participants’ separate evaluations of individual sensory modalities across scene combinations. As shown in Table 3, all three sensory modalities demonstrated highly significant differences ($p < 0.001$) in overall scores. Furthermore, all three sensory sub-scales exhibited large effect sizes ($\eta_p^2 > 0.14$), with audition reaching 0.679. The pairwise comparison results indicate that the Nature group had the highest mean scores across all three sensory modalities, and presented significant or highly significant differences compared to the Hospital and Control groups in all comparisons, with the exception of the Control group in audition. This indicates that the Nature group’s sensory experiences psychologically provided participants with better stress recovery effects. As observed in Fig. 7, it is evident that this result primarily stems from a reversal in scores between the two groups on the “noisy-quiet” evaluation dimension. This suggests that, subjectively, some participants perceived the silent environment as more delightfully quiet than the natural soundscape. The Hospital and Control groups exhibited significant differences for audition ($p < 0.001$) and olfaction ($p = 0.038$), but not for vision. The proximity of visual scores between the Control and Hospital groups is also clearly visible in the figure. This may be attributed to the visual negativity of the hospital corridor in the Hospital group being offset by the transparency of the glass, thereby eliciting a psychological response similar to that of the solid wall in the Control group.

4.2.2. PANAS

PANAS represents the difference between recovery and baseline emotional states, reflecting the emotional changes in participants before and after experiencing the scenes. It is categorized into changes in Positive Affect (PA), Negative Affect (NA), and Total Affect (PA + NA). Similar to the SPS results, as shown in Fig. 7, the Nature group scored significantly higher across all sensory modalities, followed by the Control and Hospital groups, in that order. According to Table 3, the results indicate that all three sensory modalities exhibited highly significant differences ($p < 0.001$) in PA, NA, and PA + NA scores. Furthermore, the effect sizes largely reached a large level ($\eta_p^2 > 0.14$), with only vision in NA exhibiting a moderate effect size ($\eta_p^2 = 0.135$). Pairwise comparison results demonstrate that the Hospital and Nature groups across all three senses showed highly significant differences ($p < 0.001$) in PA, NA, and PA + NA. The Control and Nature groups also exhibited significant differences across all combinations, whereas the Hospital and Control

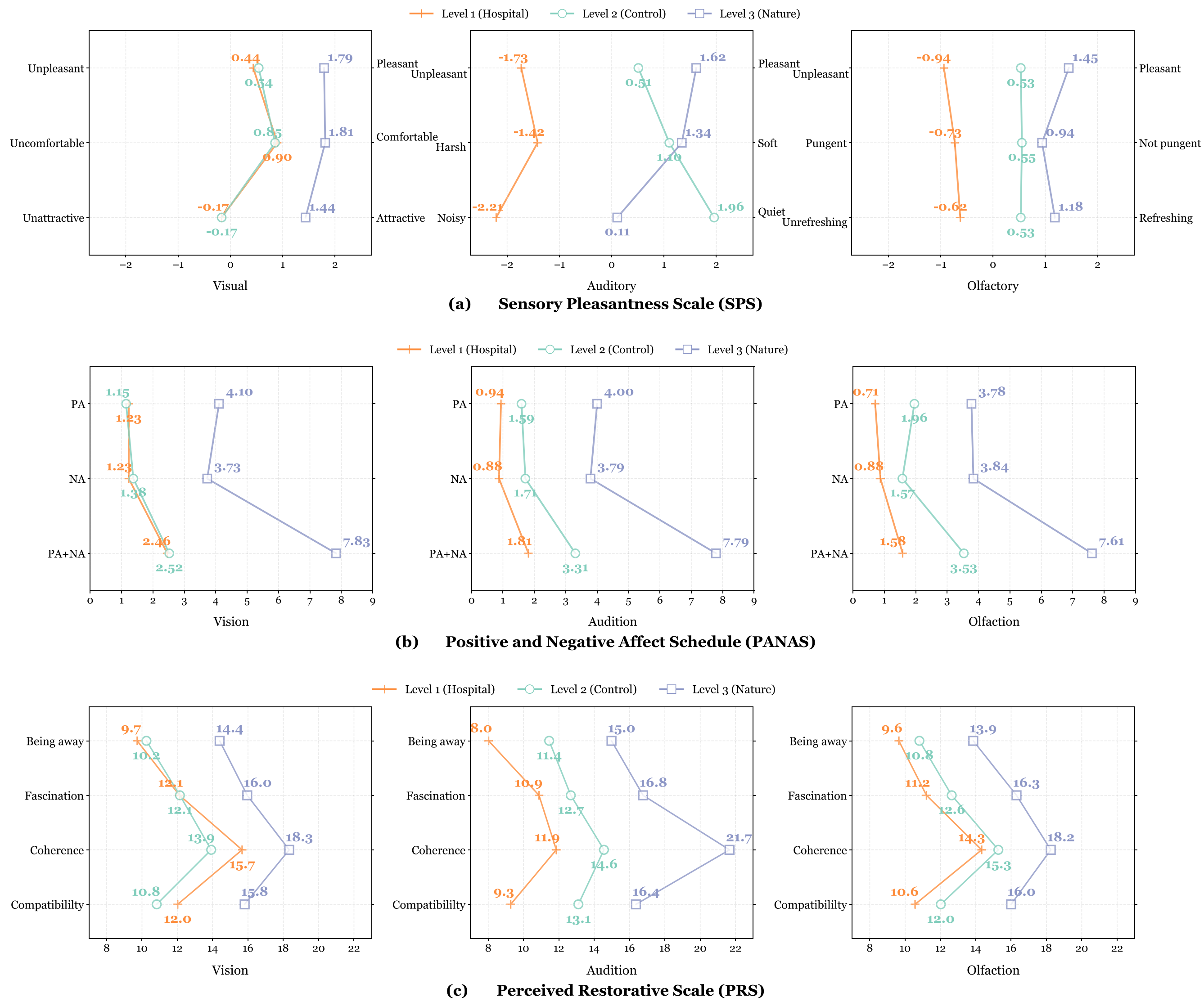

Fig. 7. Mean scores of the three psychological scales: (a) SPS, (b) PANAS and (c) PRS.

groups consistently did not show significant differences. In Fig. 7, it can be intuitively observed that the line plots for the Hospital and Control groups are in close proximity.

4.2.3. PRS

The PRS scale reflects the restorative perceptions elicited in participants by the sensory combinations of different scenes. The Nature group still achieved the best pressure recovery effect, as shown in Fig. 7. As shown in Table 3, all three sensory modalities demonstrated highly significant differences ($p < 0.001$) across every dimension. Regarding effect sizes, the values for all sensory modalities across all dimensions consistently demonstrated large effect sizes ($\eta_p^2 > 0.14$). Pairwise comparisons reveal that the Nature group exhibited significant differences from the other two groups in all instances without exception. Conversely, with the exception of certain dimensions within audition, no significant differences were found between the Hospital and Control groups.

4.3. Physiological data analysis

Fig. 8 displays the changes in all physiological indicators after experiencing the sensory combinations, with the y-axis representing the standardized value changes. For each indicator, results for vision, audition and olfaction are displayed from left to right. The three violin plots in each section represent the three levels of a specific sensory factor, reporting the mean value, median, and range within 1.5 IQR for the indicators at each level. Significance annotations are derived from the significance results of pairwise comparisons between groups following the ANOVA test.

Table 4 reports the results of the Mixed ANOVA for the physiological indicators, including the degrees of freedom (df_1, df_2), test statistics (F), Bonferroni-corrected significance (p-value), and effect size (η_p^2). Consequently, post-hoc pairwise comparisons based on EMMs were conducted to identify specific between-group differences. The mean differences (ΔEMM), standard errors (SE), test statistics (t), Bonferroni-corrected significance (p-value), and effect size (Cohen's d) for each comparison are also provided for reference (Appendix Table E).

4.3.1. EDA

The EDA data include three indicators, SCL, SCR, and SCL Rect50%, reflecting the skin conductance response of participants before and after experiencing the sensory combinations. As shown in Table 4, all three sensory modalities exhibited highly significant differences ($p < 0.001$) across the three indicators. While vision and audition demonstrated large effect sizes ($\eta_p^2 > 0.14$) across all variables, olfaction consistently exhibited moderate effect sizes ($0.06 \le \eta_p^2 < 0.14$). Notably, the effect

Table 3
Mixed ANOVA and effect sizes for the psychological scales (V: vision, A: audition, O: olfaction).

Scale	Dependent variables	Factors	*F*-value ($df = 2137$)	*p*-value	Effect size (η_p^2)
SPS	Visual	V	26.871	<0.001***	0.282
		A	7.901	<0.001***	0.103
		O	2.775	0.062 n.s.	0.039
	Auditory	V	1.200	0.301 n.s.	0.017
		A	144.918	<0.001***	0.679
		O	0.382	0.682 n.s.	0.006
	Olfactory	V	2.418	0.089 n.s.	0.034
		A	3.107	0.045*	0.043
		O	41.455	<0.001***	0.377
	Overall	V	9.987	<0.001***	0.127
		A	53.169	<0.001***	0.437
		O	16.954	<0.001***	0.198
PANAS	PA	V	16.255	<0.001***	0.192
		A	13.704	<0.001***	0.167
		O	13.800	<0.001***	0.168
	NA	V	10.653	<0.001***	0.135
		A	11.702	<0.001***	0.146
		O	13.423	<0.001***	0.164
	PA + NA	V	25.360	<0.001***	0.270
		A	24.138	<0.001***	0.261
		O	26.170	<0.001***	0.276
PRS	Being away	V	24.414	<0.001***	0.263
		A	45.029	<0.001***	0.397
		O	19.468	<0.001***	0.221
	Fascination	V	14.522	<0.001***	0.175
		A	26.967	<0.001***	0.282
		O	22.192	<0.001***	0.245
	Coherence	V	13.498	<0.001***	0.165
		A	71.617	<0.001***	0.511
		O	13.053	<0.001***	0.160
	Compatibility	V	19.026	<0.001***	0.217
		A	35.260	<0.001***	0.340
		O	24.721	<0.001***	0.265
	Overall	V	36.379	<0.001***	0.347
		A	91.802	<0.001***	0.573
		O	42.152	<0.001***	0.381

$\eta_p^2 < 0.01$ = negligible; $0.01 \le \eta_p^2 < 0.06$ = small; $0.06 \le \eta_p^2 < 0.14$ = moderate; $\eta_p^2 \ge 0.14$ = large.

sizes for vision on SCL and SCL Rect50% both exceeded 0.25, making them the most prominent; audition followed, while the olfactory effect size remained within the moderate range ($0.06 \le \eta_p^2 < 0.14$). From Fig. 8, it is evident that the Nature group had the lowest mean values across all three indicators and showed significant differences compared to the Hospital group, indicating that the stress recovery capability of the Nature group was significantly superior. Furthermore, except for olfaction of SCL, the Nature group also showed significant differences compared to the Control group. Differences between the Hospital and Control groups were significant only in the visual and olfactory dimensions of SCL, and the auditory dimension of SCR. Interestingly, regarding vision, the indicators for the Hospital group were consistently lower than those of the Control group, whereas in the other two dimensions they were higher than the latter, suggesting that participants visually perceived the hospital scene as more restorative.

4.3.2. HRV

The HRV data comprise two time-domain (RMSSD, SDNN) and one frequency-domain indicator (LF/HF). These comprehensively represent the participants' SNS and PNS recovery after experiencing the scenes. According to Table 4, the three indicators across the three senses also all showed significant differences. The effect size for vision remained the highest overall, falling within the moderate range ($0.06 \le \eta_p^2 < 0.14$), whereas audition and olfaction exhibited moderate to small effect sizes. As shown in Fig. 8, the mean LF/HF of the Nature group was the smallest, indicating that the participants' ANS balance shifted towards parasympathetic dominance, resulting in better stress recovery effects. The mean values of RMSSD and SDNN were the largest, indicating that vagal tone recovered more fully and the heart was responsive to relaxation signals. The values for the Nature and Hospital groups showed significant differences across all dimensions. The Control and Nature groups showed significant differences in vision for LF/HF and RMSSD, but not in audition and olfaction, suggesting that a silent or odorless environment can also play certain roles in stress recovery. Similar to the EDA results, no significant differences were observed between the Control and Hospital groups.

4.3.3. BP, PR & SPO_2

These three physiological indicators reveal signs of recovery in the circulatory system. BP was further categorized into SBP and DBP. As indicated in Table 4, SpO_2 remained stable across all conditions and phases. Mean values were consistently within the normal range (97-99%), and no significant main or interaction effects were observed (all $p > 0.10$). This stability indicates that the experimental procedures did not compromise systemic oxygenation or cardiopulmonary stability. Conversely, regarding BP and PR, significant differences were observed across all three sensory modalities. The effect sizes for vision and olfaction were relatively larger, falling within the moderate-to-large range (with olfaction on PR reaching 0.203), whereas the effect sizes for audition hovered around the threshold for a moderate effect.

As shown in Fig. 8, the mean values for BP and PR across all sensory modalities in the Nature group remained the lowest, representing the optimal recovery effect, followed sequentially by the Control and Hospital groups. However, for vision, the mean value for the Hospital group remained lower than that of the Control group. Regarding the significance of pairwise comparisons, the differences between the Nature group and the Hospital group remained significant across all indicators, while there was still no significant difference between the Control and Hospital groups. For audition, the Control group also did not exhibit a significant difference from the Nature group, suggesting that variations in audition have a relatively minor impact on BP and PR indicators.

4.4. Qualitative analysis

In interviews regarding multisensory stress recovery, participants expressed various spatial usage experiences extending beyond just the visual, auditory, and olfactory senses. Specifically, the largest number of individuals explicitly mentioned visual perceptions, involving lighting, indoor greenery, color tones and temperature, and decorative patterns; followed by auditory mentions, involving noise interference, sound insulation, and the zoning of active and quiet areas; and olfactory mentions, involving ventilation and odors. As evident from the word cloud (Fig. 9(a)), the most frequently cited terms included “space,” “rest,” and “insufficient,” indicating that many healthcare facilities currently face severe comfort gaps and a critical lack of break spaces.

Many evaluations and suggestions from healthcare staff regarding break spaces explicitly highlighted the importance of multisensory experiences. For instance, regarding vision:

“Visual relaxation is very important; if the overall wall patterns or design elements are too numerous, they can easily induce anxiety.”

“Cool tones easily remind medical staff of their working environment; it is suggested to use warm tones and non-blue or white color designs that do not evoke associations with the work environment.”

“It is best to have windows to receive natural light, along with green plants.”

Regarding audition:

“Use adjustable blackout curtains to create small private spaces; use sound-absorbing panels for walls, doors, and windows, and set up ’quiet’ signs at the entrance to reduce external noise interference.”

In post-test interviews with 32 participants, 14 individuals each mentioned perceptions related to audition and olfaction, while 9 mentioned

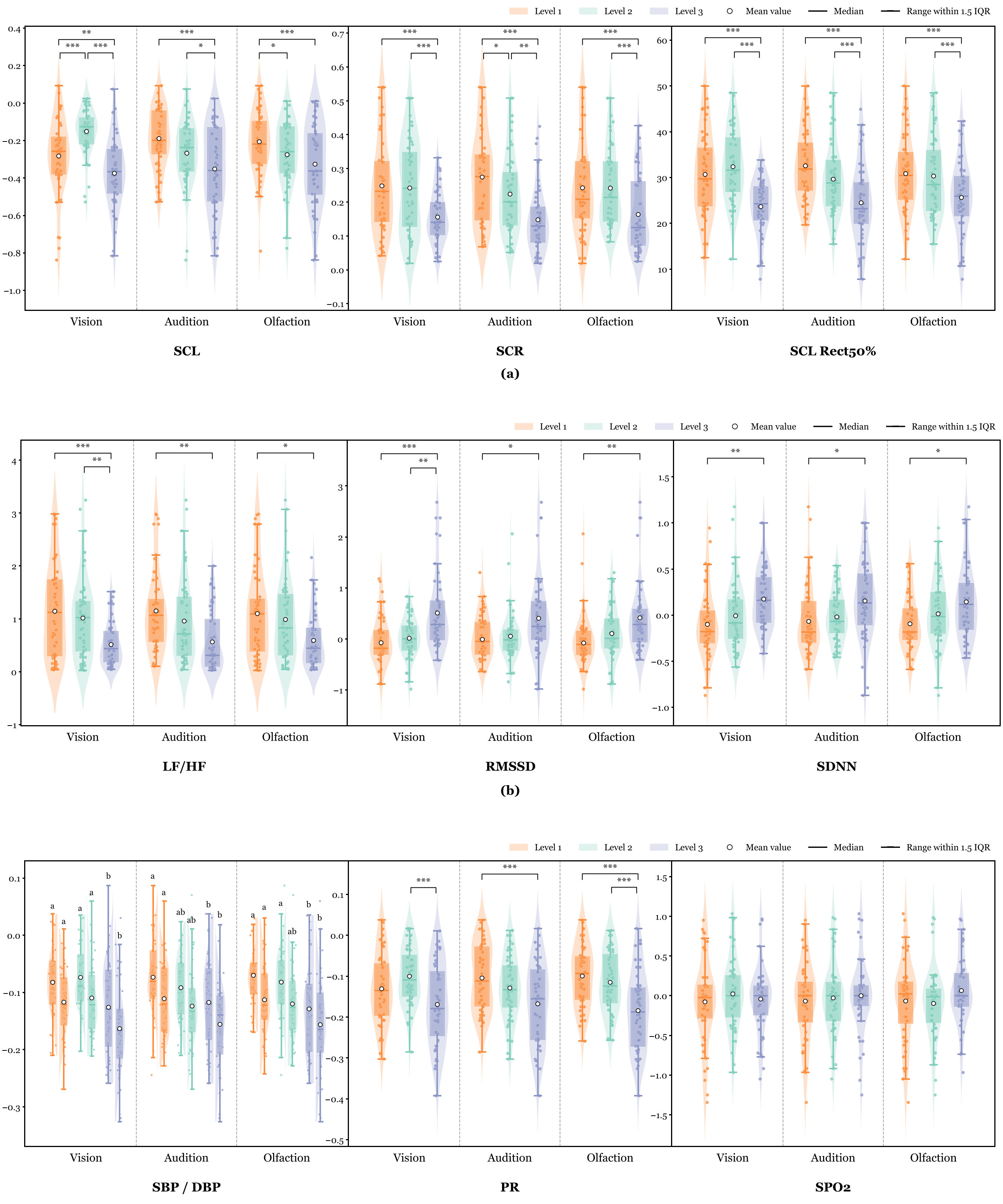

Fig. 8. Physiological results of the different combinations of senses and scenes: (a) EDA variables, (b) HRV variables, (c) BP, PR & SPO_2 variables.

vision (Fig. 9(b)). This suggests that auditory and olfactory perceptions exert a significant influence on participants in real-world environments. Some participants explicitly expressed that a specific sensory experience could affect other sensory experiences, forming a degree of "synesthetic experience," wherein negative auditory and olfactory perceptions appeared to generate more negative impacts than visual ones. For example, participants noted:

"A pleasant smell feels relatively important because real-world odors are hard to filter out. Visually, tidiness is sufficient; it doesn't necessarily have to be beautiful, but a bad smell ruins everything."

"Auditory pleasure is very important; lower environmental noise or the absence of sharp sounds can make people more relaxed. It is best to keep the environment clean and the air fresh to facilitate smooth breathing."

Notably, this relative emphasis on sounds and smell perfectly aligns with the psychological results: audition and olfaction play a more critical role in subjective perception. This contrasts with the results of the physiological indicators, seemingly implying differences in the pathways and mechanisms of subjective versus objective feedback.

Furthermore, based on their multisensory scene experiences, participants offered several suggestions for stress recovery: visual: indoor and outdoor greenery, good natural lighting, and soft colors; auditory: sound insulation, avoidance of noise or absolute silence, with acceptance of white noise or music; olfactory: removal of odors, potential addition of natural light fragrances, and good ventilation. These suggestions supplement the psychophysiological data, affirming that all senses play significant roles in stress recovery. In particular, it is essential to value auditory and olfactory perceptions, rather than solely focusing on traditional visual aspects. Participants mentioned the physical and mental relaxation effects of natural elements, such as plants and light natural scents, across all senses, providing collateral evidence that the Nature group exerts positive restorative effects across all sensory modalities.

Table 4
Mixed ANOVA and effect sizes for the physiological indicators (V: vision, A: audition, O: olfaction).

Dependent variables	Factors	F-value ($df = 2137$)	p-value	Effect size (η_p^2)
SCL	V	29.488	<0.001***	0.301
	A	12.678	<0.001***	0.156
	O	9.653	<0.001***	0.124
SCR	V	12.913	<0.001***	0.159
	A	18.453	<0.001***	0.212
	O	9.913	<0.001***	0.126
SCL Rect50%	V	25.695	<0.001***	0.273
	A	19.464	<0.001***	0.221
	O	10.848	<0.001***	0.137
LF/HF	V	7.925	<0.001***	0.104
	A	5.670	0.003**	0.076
	O	4.668	0.009**	0.064
RMSSD	V	9.807	<0.001***	0.125
	A	3.794	0.023*	0.052
	O	6.062	0.002**	0.081
SDNN	V	5.518	0.004**	0.075
	A	3.223	0.040*	0.045
	O	3.791	0.023*	0.052
PR	V	6.850	0.001**	0.091
	A	8.311	<0.001***	0.108
	O	17.497	<0.001***	0.203
SBP	V	4.675	0.009**	0.064
	A	4.141	0.016*	0.057
	O	9.251	<0.001***	0.119
DBP	V	6.909	0.001***	0.092
	A	4.234	0.015*	0.058
	O	4.540	0.011*	0.062
SPO_2	V	0.921	0.398 n.s.	0.013
	A	0.120	0.887 n.s.	0.002
	O	1.184	0.306 n.s.	0.017

$\eta_p^2 < 0.01$ = negligible; $0.01 \le \eta_p^2 < 0.06$ = small; $0.06 \le \eta_p^2 < 0.14$ = moderate; $\eta_p^2 \ge 0.14$ = large.

4.5. Cumulative synergy of multisensory stimuli in stress recovery

A variance contribution analysis was conducted to explicitly quantify the relative impact of individual sensory modalities and their combined effects. The results demonstrate that different sensory modalities act as robust and independent drivers in the stress recovery process, exhibiting profound cumulative synergy.

Fig. 10 illustrates the proportion of the Sum of Squares (SS) for the main effects, pooled interactions, and residual errors. The data reveal distinct, hierarchical contributions between psychological and physiological indicators: Audition (26.0%) and Olfaction (13.2%) dominate psychological variance over Vision (11.8%), whereas Vision (10.0%) leads physiological responses over Audition (7.6%) and Olfaction (6.9%). Furthermore, variance contributions within the SPS subscales precisely matched their corresponding stimuli (Vision: 25.0%, Audition: 67.6%, Olfaction: 36.5%), robustly validating the questionnaire's reliability. Notably, the overall explained variance is substantially higher for psychological (52.1%) than physiological indicators (29.5%). This indicates that subjective psychological responses are more directly interpretable and shaped by sensory interventions, whereas physiological stress recovery involves more complex and variable internal regulatory mechanisms.

Crucially, the average variance contribution of the pooled interactions is extremely minimal across both dimensions (psychological: 1.1%; physiological: 4.9%). This lack of statistical interference effectively validates that the positive effects of nature-based visual, auditory, and olfactory stimuli do not overshadow or conflict with one another. Instead, they operate simultaneously with an additive nature. Although the trends of influence are consistent between individual sensory treatments and combined multisensory treatments, a specific sensory modality should by no means be treated in isolation; instead, the different modalities must be viewed as an integrated whole to achieve maximum cumulative restorative capacity.

4.6. Correlation between psychological and physiological responses

A comprehensive analysis of the psychological and physiological results allows for a more precise identification of the stress recovery effects associated with different sensory modalities and experimental groups. Prior to the analysis, Z-scores were calculated for each psychological and physiological indicator to standardize the variables and facilitate concurrent analysis. Fig. 11 displays trend charts for all indicators across different sensory groups. Each color represents an indicator of a distinct type and data source, with values of different groups connected by smooth curves.

Evidently, for audition and olfaction, the peaks and troughs of nearly every curve appear near the Hospital or Nature groups (note: physiological indicator values, with the exception of RMSSD and SDNN, are generally negatively correlated with restoration). This indicates that the disparity between these two groups is generally the greatest, while the Control group is situated between them. Conversely, for vision, the difference between the values of the Hospital and Control groups appears generally minimal, yet both exhibit a distinct gap compared to the values of the Nature group. The highly consistent trend across different indicators demonstrates that the Nature group settings for visual, auditory, and olfactory senses all provide the optimal stress recovery effects.

Fig. 12 illustrates the overall macroscopic correlations between various psychological and physiological indicators across all pooled observations, employing Pearson's r as the correlation coefficient and adopting the definition of correlation strength from Cohen [15]. As observed in the figure, with the exception of SpO_2, which exhibited low correlations with other indicators due to insignificant between-group differences, the remaining indicators all demonstrated correlations ranging from small to large. Distinct moderate-to-large correlations were

Fig. 9. Word cloud analysis of the two interviews from: (a) healthcare professionals, (b) experiment participants.

observed between the various dimensions of the psychological scales, generally exhibiting high statistical significance; for example, between PA + NA and Overall-PRS ($r = 0.67, p < 0.001$). Correlations between dimensions within the same scale were even larger, such as between PRS-Fascination and PRS-Compatibility ($r = 0.70, p < 0.001$), reflecting the rationality and coherence of the scale design.

Compared to the psychological scale indicators, correlations among physiological indicators were relatively smaller, mostly manifesting as small-to-moderate correlations. Nonetheless, substantial correlations were still observed between certain indicators with generally significant results, such as between SCL and SBP ($r = 0.38, p < 0.001$). Similarly, correlations between indicators within the same category of physiological variables were larger, such as between SDNN and RMSSD ($r = 0.70, p < 0.001$). This phenomenon is understandable, as physiological indicators, compared to psychological ones, are subject to greater interference from internal and external bodily factors and exhibit more sensitive dynamic changes.

Correlations between psychological and physiological indicators predominantly manifested as moderate, such as between SCL and PRS-Coherence ($r = 0.48, p < 0.001$), and between PR and PRS-Being Away ($r = 0.45, p < 0.001$). This demonstrates strong associations between indicators, suggesting that the psychological and physiological measurement results of the experiment can be used to jointly interpret the conclusions.

5. Discussion

5.1. Comprehensive analysis of psychological and physiological results

A comprehensive joint analysis of psychological and physiological indicators reveals a high degree of overall consistency between the two. The Nature group demonstrated the optimal stress recovery effects across nearly all psychophysiological indicators within every sensory dimension. In pairwise comparisons, significant differences were predominantly observed between the Nature group and both the Control and Hospital groups, indicating that these differences are systematic and that the healing effect of the natural environment is holistic.

However, psychological indicators generally exhibited higher correlations and larger ANOVA effect sizes than physiological indicators. This suggests a psychophysiological desynchrony caused by physiological latency; subjective perceptions typically occur more rapidly and stably than changes in metrics like HRV, EDA, or notably SpO_2, which yielded no significant short-term differences. This phenomenon is corroborated by the variance analysis, where psychological variables presented notably smaller residual errors, implying higher explainability. While physiological indicators are highly susceptible to unpredictable internal homeostatic fluctuations and external disturbances, psychological indicators rely on subjective cognition, which effectively filters these subtle interferences to produce more stable outcomes. These distinct yet complementary characteristics underscore the advantage of a combined analysis, as it simultaneously captures complex conscious appraisals and low-level subconscious autonomic (SNS and PNS) arousal, providing comprehensive feedback on an individual's overall stress recovery.

Furthermore, subtle distinctions exist within the psychological indicators themselves. Based on the peak effect sizes, the magnitude generally ranked as PANAS < PRS < SPS. This implies that altering core emotions (PANAS, with η_p^2 up to 0.276) is relatively more difficult, requiring longer durations or stronger stimuli than altering perceived restorativeness (PRS, with η_p^2 up to 0.573). Conversely, explicit cognitive evaluations of targeted sensory pleasantness (SPS, with η_p^2 peaking at an impressive 0.679 for audition) are the most direct and responsive to environmental changes.

5.2. Differential stress restorative effects across sensory groups

Our data confirm the significant effectiveness of natural sensory combinations in facilitating stress recovery among healthcare professionals, aligning with ART and SRT. By exhibiting the greatest divergence from the clinical environment, the Nature group provided profound "psychological detachment" and a sense of "being away." This facilitated a substantial shift in attention, allowing individuals to completely disengage from the high-pressure work mindset. From the evolutionary perspective of biophilia, natural sounds (e.g., birdsong, flowing water) signal "safety" and "resource abundance," offering a primitive sense of security crucial for staff constantly in a "fight-or-flight" state. Concurrently, natural scents (e.g., plants, soil) directly regulate the ANS via the limbic system, bypassing cognitive processing to induce non-cognitive physiological relaxation.

Beyond the Nature group, differences between the Control and Hospital groups were largely non-significant. While audition and olfaction generally followed a Nature > Control > Hospital restorative ranking, vision exhibited a Nature > Hospital > Control trend, albeit with a negligible gap between the latter two (as evident in the psychological scales). This discrepancy likely stems from an inherent human preference for visual permeability. Although the Hospital group featured a depressing corridor view, its large floor-to-ceiling glass window provided greater openness than the Control group's solid wall, partially offsetting the negative visual content.

Notably, certain indicators (e.g., SPS-auditory, SDNN for audition and olfaction) revealed relatively small differences between the natural stimuli and the blank control conditions. This offers an important practical insight: for healthcare professionals chronically exposed to negative clinical environments, the mere absence of noise and odors is inherently an improvement. Removing stressors constitutes the critical first step, followed by the introduction of restorative natural elements. Thus, under constrained conditions, prioritizing the elimination of negative sensory factors can already enhance the perceived experience.

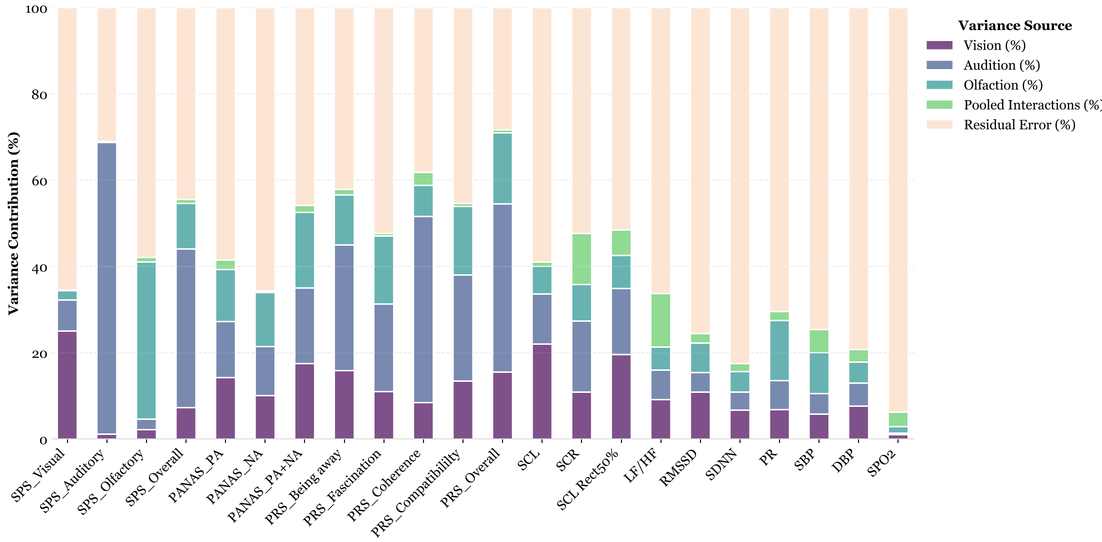

Fig. 10. Variance contribution of sensory main effects, pooled interactions, and residual errors across all psychophysiological indicators.

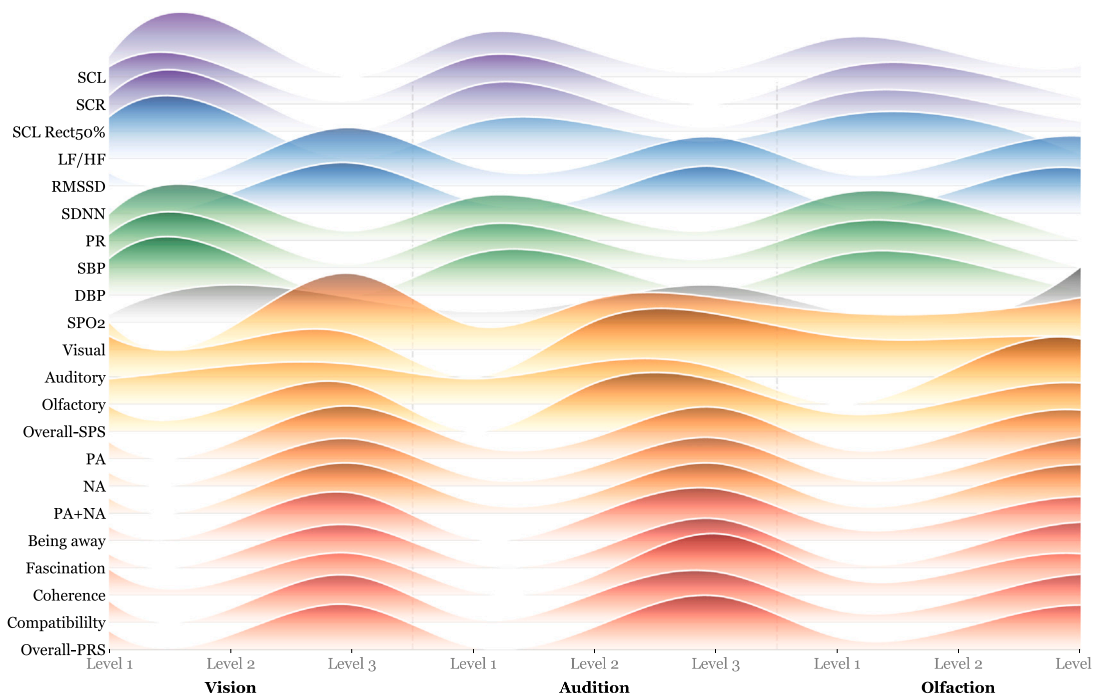

Fig. 11. Trends in psychological and physiological indicators under different combinations of senses and groups.

5.3. Sensory hierarchy and contributions of different senses to stress recovery

The analysis of multisensory integration explicitly indicates that the senses exhibit strong, independent, and additive effects rather than functioning in complex conditional isolation. This cumulative synergy not only explains the most prominent stress recovery effect observed in the full-sensory Nature group but also reflects the effect of sensory congruency. Consistent, non-interfering perceptual inputs enhance immersion and restorative efficacy, whereas sensory conflict or missing modalities disrupt this harmony and compromise recovery.

Variance contributions precisely delineate each sense's role in stress relief, revealing a structural divergence: Vision (10.0%) dominates the physiological baseline (Audition: 7.6%, Olfaction: 6.9%), whereas Audition (26.0%) and Olfaction (13.2%) overwhelmingly dominate subjective psychological emotions over Vision (11.8%). This intriguing conclusion adds a nuanced layer to the classic Sensory Hierarchy Theory, which posits that when humans perceive and process external information, there are differences in priority and contribution among different sensory channels [86]. In contrast to the traditional view of vision accounting for over 70% of general human sensory input [37], our explicit variance data reveal that this absolute visual dominance is significantly attenuated during the stress recovery process. Instead of dictating subjective restoration, vision recedes to exert a continuous regulatory effect on autonomic arousal, functioning primarily as the physiological baseline. In contrast, a structural "hierarchy reversal" may occur in emotional assessments and subjective awareness. Audition and olfaction possess a "veto power," carrying significantly higher weight in

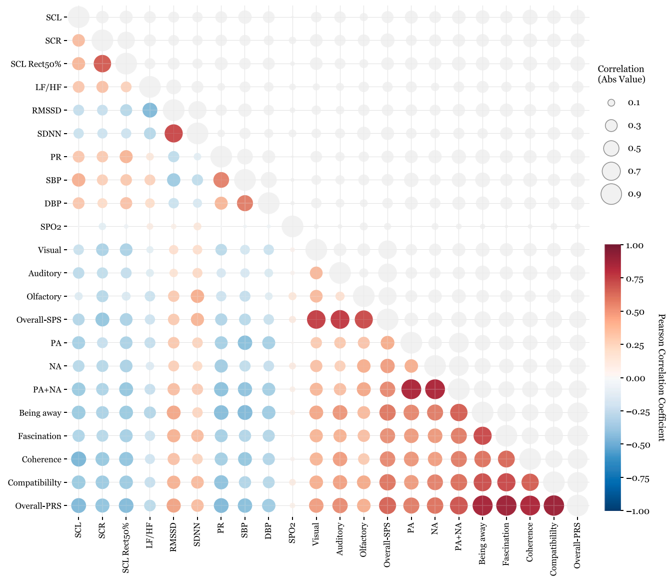

Fig. 12. Correlation between psychological and physiological data results. $|r| < 0.10$ = negligible; $0.10 \le |r| < 0.30$ = small; $0.30 \le |r| < 0.50$ = moderate; $|r| \ge 0.50$ = large.

subjective perception due to their intrusiveness: humans can close their eyes to shut out visual input, but cannot close their ears or stop breathing. Consequently, adverse sounds and smells are more likely to trigger a binary judgment of comfort, thereby generating strong subjective negative emotional evaluations and determining the affective quality of the experience.

This phenomenon is also elucidated by the Proust Effect: olfaction can induce autobiographical memories and emotional responses more vividly and directly than vision [13]. The limbic system, which processes emotions and olfaction, is activated upon stimulation by odors, directly awakening emotional memories associated with the scent and amplifying the negative or positive valence of the sensory experience. Additionally, the higher uninterpretable residual error observed in physiological indicators (70.5%) compared to psychological ones (47.9%) suggests that physiological stress recovery is governed by highly complex internal homeostatic mechanisms, whereas subjective psychological restoration is more direct and responsive to targeted sensory inputs. Furthermore, the critical roles of audition and olfaction provide practical implications for the design of real-world hospital staff spaces: given limited budgets and the difficulty of structural visual modifications (e.g., altering walls or windows), introducing low-cost soundscape and smellscape interventions represents a highly cost-effective strategy to enhance staff satisfaction.

5.4. Limitations and future works

Subject to certain objective constraints, this study presents several limitations. First, the representativeness of the participant group warrants discussion. Due to the high temporal and spatial costs of stress recovery experiments, recruiting frontline healthcare professionals in batches was difficult. Therefore, as an exploratory study, adult university students and staff were recruited. Although the experimental scenarios were relatively novel to any group, medical staff are chronically exposed to high-load and high-risk work environments, and their baseline stress levels and sensitivity to environmental stimuli might slightly differ from those of students. At the same time, the formal experiment tested multi-sensory conditions that had been derived from frontline healthcare professionals' preferences and evaluations, so the present sample should be understood as a controlled proxy for examining the short-term restorative effects of healthcare-informed sensory cues rather than as a full substitute for the target population. The current sample may not fully simulate the specific psychological stress responses triggered by occupational burnout in medical staff towards specific sensory cues.

Second, although virtual environments simulate reality to the maximum extent, a simplification of variable settings is still inevitable, making it difficult to fully replicate the sensory complexity of real environments, particularly regarding the selection of experimental sounds and scents. For instance, hospital noise was unified into a single mixed audio track; however, real noise characteristics across different departments (e.g., ICU alarms vs. outpatient clinic clamor) may have varying impacts on stress. Similarly, the virtual scents in the experiment were relatively singular and constant, whereas odors in real hospitals are more mixed and dynamic.

Third, the experimental methodology faced two primary constraints related to procedural continuity and measurement comprehensiveness. First, requiring participants to remove the VR headset to complete questionnaires introduced a physical transition that likely triggered a break in presence (BIP). This interruption may have accelerated the decay of psychological states elicited by the virtual environment, potentially confounding subsequent responses on the SPS, PANAS, and PRS [2]. Second, the study did not incorporate standardized immersion metrics, such as the IPQ, SUS, or SSQ [52,89,95], which limited the ability to quantify the depth of the immersive experience. To address these limitations, future research should optimize the protocol by integrating in-VR data collection and employing established immersion scales. These refinements would support a more robust, multidimensional evaluation of the synergy between multisensory stimuli and restorative outcomes.

Finally, there are differences in stress types and induction methods between the laboratory environment and the real hospital environment. The mathematical tasks in the experiment induced acute cognitive stress, whereas medical staff often face contextual chronic emotional stress or traumatic stress arising from realistic clinical demands related to life-and-death situations. This distinction is crucial because the source and ecological specificity of stressors shape how restorative environments are perceived and how physiological recovery unfolds. Abstract cognitive load under controlled laboratory conditions may not fully capture the emotionally embedded and situationally complex stress profile associated with occupational burnout in healthcare settings. However, such chronic and context-specific stress remains difficult to simulate within a tightly controlled experimental cycle. To address this limitation, future studies could develop more ecologically grounded multisensory immersive stress paradigms for healthcare settings, in which stress is embedded directly into realistic clinical scenarios and assessed with additional measures sensitive to complex emotional responses, such as EEG, alongside peripheral physiological indicators [6,70].

Future work can address the limitations of this study by recruiting frontline healthcare professionals for experiments in real hospital environments. Conducting field studies and collecting data during the actual break intervals of medical staff can validate the effectiveness of laboratory conclusions in real-world scenarios. More complex sensory variables can be introduced, such as distinguishing the non-linear effects of different noise frequencies and scent concentrations on stress. More importantly, these results have substantial application value for designing and renovating staff break spaces. Architects and interior designers can translate the results and findings of this study into actionable design principles, thereby improving the working environment for healthcare professionals. Future hospital design should not merely stop at "visible" restoration, but should instead shift towards the construction of a "hearable and smellable" multisensory ecosystem.

6. Conclusion

By integrating a virtual space design process grounded in staff preferences, an orthogonal experimental design, and mixed-effects psychophysiological analyses, this study investigated how the multisensory environment of hospital staff break spaces influences stress recovery.

Overall, natural sensory conditions produced the most effective stress recovery across nearly all psychological and physiological measures. The ranking of the Hospital and Control groups varied slightly by modality, though differences between them were largely non-significant. Our findings reveal that restorative effects arise from a cumulative synergy, demonstrating that visual, auditory, and olfactory channels exert robust, independent, and additive benefits rather than complex conditional interactions. Furthermore, a distinct sensory hierarchy emerged: visual stimuli primarily established the physiological baseline for autonomic arousal, whereas auditory and olfactory cues overwhelmingly dictated affective evaluations and subjective feelings of restoration. Taken together, the present study suggests that transforming staff break spaces into holistic multisensory restorative environments organized around natural cues offers a realistic and feasible pathway to substantially improve stress recovery and mitigate occupational burnout for healthcare professionals.

CRediT authorship contribution statement

Dalin Lyu: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hengyi Cong:** Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Sipu Zhu:** Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Yulong Liu:** Writing – review & editing, Supervision, Methodology. **Weimin Zhuang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Investigation, Data curation, Conceptualization.

Ethics statement

Ethics approval was obtained from the Tsinghua University Ethics Committee. In addition, we have obtained the participants' permission and consent to participate in this study.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Basic information about the participants in the spatial preference survey and the formal experiment is presented in Tables A and B, respectively.

Table A
Participant demographics of the preference survey.

Demographics	Category	Count	Percentage
Gender	Male	37	20.56%
	Female	143	79.44%
Age	20–29	37	20.56%
	30–39	58	32.22%
	40–49	58	32.22%
	50–59	27	15.00%
Possessed degree	Undergraduate	102	56.67%
	Postgraduate	78	43.33%
Occupation	Doctor	71	39.44%
	Nurse	72	40%
	Administrative staff	18	10%
	Medical student	17	9.44%
	Other	2	1.11%
Art-related education or training	Yes	22	12.22%
	No	158	87.78%

Table B
Participant demographics of the experiment.

Demographics	Category	Count	Percentage
Gender	Male	30	41.67%
	Female	42	58.33%
Age	18–24	39	54.17%
	25–29	24	33.33%
	30–34	7	9.72%
	35–39	2	2.78%
Possessed degree	High school or below	6	8.33%
	Undergraduate	35	48.61%
	Postgraduate	31	43.06%
Art-related education or training	Yes	10	13.89%
	No	62	86.11%
Corrective lenses	Yes	54	75.00%
	No	18	25.00%
Vision problems	Myopia	59	81.94%
	Hyperopia	3	4.17%
	Astigmatism	43	59.72%
	Color Blindness	1	1.39%
	Color Amblyopia	1	1.39%
	No problem	11	15.28%

Appendix B

Complementary statistical results are shown in this section for reference. Chi-squared goodness-of-fit test results for factor preferences across space types are shown in Table C. Paired comparison results (T-test/Mann-Whitney U test) and the effect sizes of the psychological and physiological indicators, respectively in Tables D and E.

Table C
Chi-squared goodness-of-fit test results for factor preferences across space types.

Space types	Like/dislike	Factors	Chi-squared (χ^2)	df	*p*-value
Enclosed	Most liked	Contour	128.000	1	$< 0.001^{***}$
		Color	498.203	2	$< 0.001^{***}$
		Texture	220.413	2	$< 0.001^{***}$
		Openness	34.722	1	$< 0.001^{***}$
	Most disliked	Contour	3.736	1	0.053 n.s.
		Color	710.253	2	$< 0.001^{***}$
		Texture	308.010	2	$< 0.001^{***}$
		Openness	10.889	1	0.001^{***}
Open	Most liked	Contour	63.469	1	$< 0.001^{***}$
		Color	204.040	2	$< 0.001^{***}$
		Texture	15.190	2	$< 0.001^{***}$
		Openness	50.669	1	$< 0.001^{***}$
	Most disliked	Contour	39.902	1	$< 0.001^{***}$
		Color	441.930	2	$< 0.001^{***}$
		Texture	24.063	2	$< 0.001^{***}$
		Openness	82.776	1	$< 0.001^{***}$
Centralized	Most liked	Contour	247.902	1	$< 0.001^{***}$
		Color	357.213	2	$< 0.001^{***}$
		Texture	63.743	2	$< 0.001^{***}$
		Openness	18.000	1	$< 0.001^{***}$
	Most disliked	Contour	19.220	1	$< 0.001^{***}$
		Color	607.590	2	$< 0.001^{***}$
		Texture	49.803	2	$< 0.001^{***}$
		Openness	7.220	1	0.007^{**}

(continued on next page)

Table D
Estimated marginal means (EMMs) pairwise comparisons and effect sizes for the psychological scales (V: vision, A: audition, O: olfaction).

Scale	Dependent variables	Factors	Levels	Mean difference (ΔEMM)	Standard error (SE)	*t*-value (df = 137)	*p*-value	Effect size (Cohen's *d*)
SPS	Visual	V	1 vs. 2	0.466	0.622	0.748	1.000 n.s.	0.128
			1 vs. 3	−3.694	0.623	−5.926	<0.001***	−1.013
			2 vs. 3	−4.159	0.621	−6.699	<0.001***	−1.145
		A	1 vs. 2	−2.061	0.618	−3.337	0.003**	−0.57
			1 vs. 3	−2.246	0.634	−3.545	0.002**	−0.606
			2 vs. 3	−0.185	0.624	−0.297	1.000 n.s.	−0.051
	Auditory	A	1 vs. 2	−8.56	0.616	−13.904	<0.001***	−2.376
			1 vs. 3	−9.656	0.624	−15.468	<0.001***	−2.643
			2 vs. 3	−1.096	0.619	−1.769	0.237 n.s.	−0.302
	Olfactory	A	1 vs. 2	−1.842	0.742	−2.482	0.043*	−0.424
			1 vs. 3	−1.097	0.751	−1.462	0.438 n.s.	−0.25
			2 vs. 3	0.744	0.74	1.006	0.948 n.s.	0.172
		O	1 vs. 2	−3.923	0.744	−5.274	<0.001***	−0.901
			1 vs. 3	−6.797	0.75	−9.06	<0.001***	−1.548
			2 vs. 3	−2.874	0.751	−3.827	0.001***	−0.654
	Overall	V	1 vs. 2	−0.098	1.405	−0.07	1.000 n.s.	−0.012
			1 vs. 3	−5.482	1.41	−3.887	<0.001***	−0.664
			2 vs. 3	−5.384	1.398	−3.852	0.001***	−0.658
		A	1 vs. 2	−12.416	1.396	−8.894	<0.001***	−1.52
			1 vs. 3	−12.866	1.428	−9.012	<0.001***	−1.54
			2 vs. 3	−0.45	1.401	−0.321	1.000 n.s.	−0.055
		O	1 vs. 2	−3.548	1.404	−2.528	0.038*	−0.432
			1 vs. 3	−8.153	1.403	−5.81	<0.001***	−0.993
			2 vs. 3	−4.604	1.411	−3.263	0.004**	−0.557
PANAS	PA	V	1 vs. 2	0.086	0.599	0.144	1.000 n.s.	0.025
			1 vs. 3	−2.889	0.595	−4.858	<0.001***	−0.83
			2 vs. 3	−2.975	0.596	−4.993	<0.001***	−0.853
		A	1 vs. 2	−0.621	0.598	−1.039	0.902 n.s.	−0.178
			1 vs. 3	−2.986	0.605	−4.939	<0.001***	−0.844
			2 vs. 3	−2.365	0.594	−3.984	<0.001***	−0.681
		O	1 vs. 2	−1.278	0.598	−2.138	0.103 n.s.	−0.365
			1 vs. 3	−3.125	0.598	−5.224	<0.001***	−0.893
			2 vs. 3	−1.847	0.597	−3.095	0.007**	−0.529
	NA	V	1 vs. 2	−0.088	0.633	−0.139	1.000 n.s.	−0.024
			1 vs. 3	−2.472	0.613	−4.032	<0.001***	−0.689
			2 vs. 3	−2.384	0.615	−3.876	<0.001***	−0.662
		A	1 vs. 2	−0.864	0.614	−1.407	0.485 n.s.	−0.24
			1 vs. 3	−2.883	0.613	−4.706	<0.001***	−0.804
			2 vs. 3	−2.019	0.61	−3.308	0.004**	−0.565
		O	1 vs. 2	−0.739	0.616	−1.199	0.697 n.s.	−0.205
			1 vs. 3	−3.006	0.604	−4.975	<0.001***	−0.85
			2 vs. 3	−2.267	0.614	−3.693	0.001***	−0.631
	PA + NA	V	1 vs. 2	−0.054	0.875	−0.062	1.000 n.s.	−0.011
			1 vs. 3	−5.385	0.87	−6.191	<0.001***	−1.058
			2 vs. 3	−5.331	0.871	−6.123	<0.001***	−1.046
		A	1 vs. 2	−1.455	0.885	−1.645	0.307 n.s.	−0.281
			1 vs. 3	−5.858	0.883	−6.633	<0.001***	−1.133
			2 vs. 3	−4.402	0.87	−5.059	<0.001***	−0.864
		O	1 vs. 2	−1.994	0.88	−2.266	0.075 n.s.	−0.387
			1 vs. 3	−6.135	0.867	−7.074	<0.001***	−1.209
			2 vs. 3	−4.141	0.869	−4.765	<0.001***	−0.814
PRS	Being away	V	1 vs. 2	−0.571	0.721	−0.792	1.000 n.s.	−0.135
			1 vs. 3	−4.619	0.72	−6.411	<0.001***	−1.095
			2 vs. 3	−4.048	0.721	−5.614	<0.001***	−0.959
		A	1 vs. 2	−3.404	0.723	−4.709	<0.001***	−0.805
			1 vs. 3	−6.876	0.725	−9.49	<0.001***	−1.622
			2 vs. 3	−3.472	0.726	−4.78	<0.001***	−0.817
		O	1 vs. 2	−1.168	0.725	−1.611	0.329 n.s.	−0.275
			1 vs. 3	−4.321	0.717	−6.024	<0.001***	−1.029
			2 vs. 3	−3.153	0.72	−4.377	<0.001***	−0.748
	Fascination	V	1 vs. 2	0.007	0.811	0.009	1.000 n.s.	0.002
			1 vs. 3	−3.779	0.812	−4.656	<0.001***	−0.796
			2 vs. 3	−3.786	0.81	−4.677	<0.001***	−0.799
		A	1 vs. 2	−1.799	0.805	−2.237	0.081 n.s.	−0.382
			1 vs. 3	−5.884	0.82	−7.179	<0.001***	−1.227
			2 vs. 3	−4.085	0.813	−5.023	<0.001***	−0.858
		O	1 vs. 2	−1.453	0.815	−1.783	0.230 n.s.	−0.305
			1 vs. 3	−5.19	0.805	−6.448	<0.001***	−1.102
			2 vs. 3	−3.737	0.809	−4.62	<0.001***	−0.789

(*continued on next page*)

Table D *(continued)*

Scale	Dependent variables	Factors	Levels	Mean difference (ΔEMM)	Standard error (SE)	*t*-value (*df* = 137)	*p*-value	Effect size (Cohen's *d*)
	Coherence	V	1 vs. 2	1.644	0.831	1.979	0.149 n.s.	0.338
			1 vs. 3	−2.642	0.831	−3.181	0.005**	−0.544
			2 vs. 3	−4.286	0.832	−5.149	<0.001***	−0.88
		A	1 vs. 2	−2.64	0.827	−3.194	0.005**	−0.546
			1 vs. 3	−9.685	0.836	−11.581	<0.001***	−1.979
			2 vs. 3	−7.044	0.83	−8.484	<0.001***	−1.45
		O	1 vs. 2	−0.863	0.836	−1.032	0.911 n.s.	−0.176
			1 vs. 3	−4.02	0.829	−4.848	<0.001***	−0.828
			2 vs. 3	−3.157	0.832	−3.796	0.001***	−0.649
	Compatibililty	V	1 vs. 2	1.158	0.826	1.402	0.489 n.s.	0.24
			1 vs. 3	−3.743	0.83	−4.509	<0.001***	−0.77
			2 vs. 3	−4.902	0.83	−5.909	<0.001***	−1.01
		A	1 vs. 2	−3.804	0.828	−4.595	<0.001***	−0.785
			1 vs. 3	−6.981	0.832	−8.386	<0.001***	−1.433
			2 vs. 3	−3.177	0.827	−3.84	0.001***	−0.656
		O	1 vs. 2	−1.48	0.832	−1.779	0.232 n.s.	−0.304
			1 vs. 3	−5.588	0.825	−6.777	<0.001***	−1.158
			2 vs. 3	−4.108	0.827	−4.97	<0.001***	−0.849
	Overall	V	1 vs. 2	2.228	2.173	1.026	0.921 n.s.	0.175
			1 vs. 3	−14.83	2.171	−6.831	<0.001***	−1.167
			2 vs. 3	−17.058	2.176	−7.841	<0.001***	−1.34
		A	1 vs. 2	−11.727	2.165	−5.416	<0.001***	−0.925
			1 vs. 3	−29.439	2.187	−13.461	<0.001***	−2.3
			2 vs. 3	−17.712	2.172	−8.156	<0.001***	−1.394
		O	1 vs. 2	−4.948	2.185	−2.264	0.075 n.s.	−0.387
			1 vs. 3	−19.091	2.161	−8.836	<0.001***	−1.51
			2 vs. 3	−14.143	2.171	−6.514	<0.001***	−1.113

Table E
Estimated marginal means (EMMs) pairwise comparisons and effect sizes for the physiological indicators (V: vision, A: audition, O: olfaction).

Dependent variables	Factors	Levels	Mean difference (ΔEMM)	Standard error (SE)	*t*-value (*df* = 137)	*p*-value	Effect size (Cohen's *d*)
SCL	V	1 vs. 2	−0.656	0.151	−4.347	<0.001***	−0.743
		1 vs. 3	0.503	0.151	3.323	0.003**	0.568
		2 vs. 3	1.159	0.151	7.655	<0.001***	1.308
	A	1 vs. 2	0.362	0.151	2.390	0.055 n.s.	0.408
		1 vs. 3	0.761	0.151	5.033	<0.001***	0.860
		2 vs. 3	0.400	0.151	2.647	0.027*	0.452
	O	1 vs. 2	0.385	0.152	2.530	0.038*	0.432
		1 vs. 3	0.658	0.150	4.377	<0.001***	0.748
		2 vs. 3	0.273	0.151	1.809	0.218 n.s.	0.309
SCR	V	1 vs. 2	0.080	0.160	0.501	1.000 n.s.	0.086
		1 vs. 3	0.740	0.160	4.626	<0.001***	0.791
		2 vs. 3	0.660	0.160	4.135	<0.001***	0.706
	A	1 vs. 2	0.399	0.160	2.495	0.041*	0.426
		1 vs. 3	0.965	0.160	6.046	<0.001***	1.033
		2 vs. 3	0.566	0.160	3.539	0.002**	0.605
	O	1 vs. 2	0.017	0.161	0.105	1.000 n.s.	0.018
		1 vs. 3	0.620	0.159	3.906	<0.001***	0.667
		2 vs. 3	0.603	0.160	3.778	0.001***	0.646
SCL Rect50%	V	1 vs. 2	−0.184	0.150	−1.226	0.667 n.s.	−0.210
		1 vs. 3	0.828	0.150	5.508	<0.001***	0.941
		2 vs. 3	1.013	0.151	6.728	<0.001***	1.150
	A	1 vs. 2	0.339	0.151	2.252	0.078 n.s.	0.385
		1 vs. 3	0.928	0.151	6.164	<0.001***	1.053
		2 vs. 3	0.589	0.150	3.913	<0.001***	0.669
	O	1 vs. 2	0.051	0.152	0.335	1.000 n.s.	0.057
		1 vs. 3	0.629	0.150	4.203	<0.001***	0.718
		2 vs. 3	0.578	0.152	3.808	0.001***	0.651
LF/HF	V	1 vs. 2	0.103	0.185	0.558	1.000 n.s.	0.095
		1 vs. 3	0.686	0.186	3.695	0.001***	0.631
		2 vs. 3	0.582	0.186	3.137	0.006**	0.536
	A	1 vs. 2	0.169	0.187	0.903	1.000 n.s.	0.154

(*continued on next page*)

Table E *(continued)*

Dependent variables	Factors	Levels	Mean difference (ΔEMM)	Standard error (SE)	*t*-value (*df* = 137)	*p*-value	Effect size (Cohen's *d*)
		1 vs. 3	0.609	0.187	3.252	0.004**	0.556
		2 vs. 3	0.440	0.185	2.374	0.057 n.s.	0.406
	O	1 vs. 2	0.075	0.189	0.399	1.000 n.s.	0.068
		1 vs. 3	0.521	0.185	2.819	0.017*	0.482
		2 vs. 3	0.445	0.187	2.387	0.055 n.s.	0.408
RMSSD	V	1 vs. 2	−0.191	0.186	−1.030	0.915 n.s.	−0.176
		1 vs. 3	−0.783	0.184	−4.257	<0.001***	−0.727
		2 vs. 3	−0.592	0.186	−3.174	0.006**	−0.542
	A	1 vs. 2	−0.139	0.184	−0.755	1.000 n.s.	−0.129
		1 vs. 3	−0.493	0.185	−2.671	0.025*	−0.456
		2 vs. 3	−0.354	0.184	−1.921	0.170 n.s.	−0.328
	O	1 vs. 2	−0.350	0.188	−1.857	0.196 n.s.	−0.317
		1 vs. 3	−0.639	0.184	−3.480	0.002**	−0.595
		2 vs. 3	−0.290	0.185	−1.565	0.360 n.s.	−0.267
SDNN	V	1 vs. 2	−0.262	0.192	−1.366	0.522 n.s.	−0.233
		1 vs. 3	−0.638	0.193	−3.306	0.004**	−0.565
		2 vs. 3	−0.376	0.193	−1.951	0.159 n.s.	−0.333
	A	1 vs. 2	−0.129	0.193	−0.673	1.000 n.s.	−0.115
		1 vs. 3	−0.474	0.193	−2.453	0.046*	−0.419
		2 vs. 3	−0.345	0.192	−1.795	0.225 n.s.	−0.307
	O	1 vs. 2	−0.300	0.196	−1.532	0.383 n.s.	−0.262
		1 vs. 3	−0.527	0.192	−2.749	0.020*	−0.470
		2 vs. 3	−0.227	0.192	−1.180	0.720 n.s.	−0.202
PR	V	1 vs. 2	−0.271	0.158	−1.717	0.265 n.s.	−0.293
		1 vs. 3	0.316	0.158	1.995	0.144 n.s.	0.341
		2 vs. 3	0.587	0.159	3.699	0.001***	0.632
	A	1 vs. 2	0.363	0.158	2.296	0.070 n.s.	0.392
		1 vs. 3	0.643	0.158	4.066	<0.001***	0.695
		2 vs. 3	0.280	0.158	1.775	0.234 n.s.	0.303
	O	1 vs. 2	0.240	0.159	1.510	0.400 n.s.	0.258
		1 vs. 3	0.895	0.157	5.708	<0.001***	0.975
		2 vs. 3	0.655	0.158	4.149	<0.001***	0.709
SBP	V	1 vs. 2	−0.058	0.182	−0.317	1.000 n.s.	−0.054
		1 vs. 3	0.453	0.181	2.507	0.040*	0.428
		2 vs. 3	0.511	0.184	2.775	0.019*	0.474
	A	1 vs. 2	0.339	0.181	1.868	0.192 n.s.	0.319
		1 vs. 3	0.510	0.180	2.829	0.016*	0.483
		2 vs. 3	0.171	0.181	0.946	1.000 n.s.	0.162
	O	1 vs. 2	0.242	0.181	1.331	0.557 n.s.	0.227
		1 vs. 3	0.756	0.180	4.209	<0.001***	0.719
		2 vs. 3	0.515	0.181	2.847	0.015*	0.486
DBP	V	1 vs. 2	−0.061	0.185	−0.330	1.000 n.s.	−0.056
		1 vs. 3	0.561	0.184	3.046	0.008**	0.520
		2 vs. 3	0.622	0.185	3.365	0.003**	0.575
	A	1 vs. 2	0.184	0.184	0.998	0.960 n.s.	0.171
		1 vs. 3	0.528	0.184	2.867	0.014*	0.490
		2 vs. 3	0.344	0.184	1.867	0.192 n.s.	0.319
	O	1 vs. 2	0.162	0.187	0.869	1.000 n.s.	0.148
		1 vs. 3	0.538	0.184	2.931	0.012*	0.501
		2 vs. 3	0.376	0.185	2.038	0.131 n.s.	0.348

Data availability

Data will be made available upon request.

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