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Lu, X. orcid.org/0000-0001-7344-4276, Cao, Y., Wang, Z. et al. (2 more authors) (2025) Multisensory symphony: synergistic effects of vision, audition, and olfaction on the restorative properties of hospital healing landscapes. Building and Environment, 275. 112812. ISSN 0360-1323

https://doi.org/10.1016/j.buildenv.2025.112812

Multisensory Symphony: Synergistic Effects of Vision, Audition, and Olfaction on the Restorative Properties of Hospital Healing Landscapes

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Abstract:

Rapid urbanization has led to increased stress and anxiety, heightening concerns about mental health. Hospitals are essential to provide medical treatment, and they also support patients' mental well-being. The effects of hospital healing landscapes to promote patients' mental health have been studied to some degree. Previous studies have primarily concentrated on one or two sensory modalities while overlooking the synergistic effects of visual, auditory, and olfactory stimuli. From a biophilic design approach and grounded in Attention Restoration Theory (ART) and Stress Reduction Theory (SRT), this study explores the synergistic impact of vision, audition, and olfaction on the restorative potentials of hospital healing landscapes. The rooftop garden of Nanjing Drum Tower Hospital served as a case study. Nine experimental scenarios were developed using an orthogonal experimental design. They involved a total of 270 volunteers participating in virtual reality experiments. Psychological assessments included the Semantic Differential Scale (SDS), State-Trait Anxiety Inventory State (STAI-S), and Perceived Restorativeness Scale (PRS), while physiological measures included Heart Rate (HR), Root Mean Square Successive difference (RMSSD), Skin Conductance Level (SCL), and Skin Conductance Response (SCR). The study demonstrates that hospital healing landscapes promote psychological and physiological restoration. Visual and olfactory stimuli primarily influenced psychological responses, while auditory elements mainly affected physiological reactions. Environments with high plant diversity, natural sounds, and complex plant aromas were the most effective for psychological and physiological restoration. This study highlights the importance of integrating multisensory elements in healing environments and offers new insights for the design and management of hospital healing landscapes.

Keywords: Hospital healing landscape; Biophilic Design; Vision; Audition; Olfaction; Virtual Reality

1. Introduction

The health and well-being of both present and future populations is a fundamental objective of sustainable urban development. Among the myriad facets of well-being, mental well-being emerges as a cornerstone, essential for individual happiness, resilience, societal cohesion, and productivity. Poor management of mental well-being can exacerbate physiological health issues and lead to stress-related disorders, including brain and cardiovascular diseases [1-3]. A substantial body of research has shown that proximity to natural environments contributes positively to mental health [4-9]. Building on this understanding, there has been a growing trend towards integrating natural elements into architectural spaces, aiming to enhance human mental well-being and contribute to sustainable urban development. Given the importance of natural environments for mental well-being, their integration into specific settings, such as hospitals, becomes particularly relevant.

Hospital environments are characterized by a mix of professional and non-professional areas. Professional areas include operating rooms and patient wards, while non-professional areas consist of family reception rooms and public open space [10, 11]. In recent years, the increasing number of patients, challenging working conditions for healthcare professionals, and limited per capita medical facilities have posed significant challenges in delivering high-quality care. The hospital population, comprising patients, staff, and visitors, often experiences high levels of emotional and work-related stress. Patients in particular may feel disoriented in an unfamiliar hospital setting. Inadequate landscape design can exacerbate patients' low mood or even lead to depressive symptoms [9]. Staff, burdened with intense work pressures, tend to prefer landscapes that encourage physical activity and stress relief [12]. Visitors, on the other hand, seek green spaces that offer privacy, refuge, and positive distractions away from the clinical environment, often to spend time with hospitalized loved ones [12, 13]. These complexities underscore the importance of hospital healing landscapes for user recovery, reduce stress, and care quality. Several studies have examined the impact of hospital healing landscapes using psychological and physiological indicators, consistently demonstrating their positive impact on the physical and mental well-being of diverse user groups [14-17].

Among the various strategies for designing hospital healing landscapes, sensory–

therapeutic gardens have emerged as a widely adopted approach. These gardens aim to create immersive environments that engage users through multiple sensory stimuli. Previous research on hospital healing landscape design predominantly focuses on single sensory elements, particularly visual components, while neglecting the combined effects of other senses, including auditory and olfactory experiences [16, 18]. This approach limits the therapeutic potential of the landscape to serve users effectively [18].

Natural sounds (e.g., birdsong, flowing water) and pleasant odors (e.g., plants, fresh air) have been shown to significantly enhance relaxation and emotional recovery [19, 20]. Exposure to such olfactory and auditory environments contribute to the restoration of both physical and mental well-being [21-24]. Furthermore, many studies prioritize subjective user assessments in examining the effectiveness of hospital healing landscapes, often using methods such as questionnaires or on-site visits [25, 26]. While subjective assessments provide valuable insights, they may overlook the physiological mechanisms underlying the restorative effects of healing landscapes. This oversight may lead to an incomplete understanding of the restorative mechanisms and underestimate the full potential of healing landscapes.

Given the limited research on the combined effects of visual, auditory, and olfactory elements, this research is led by the following two research questions:
RQ1. To what extent do visual, auditory and olfactory elements influence the restorative properties of hospital healing landscapes?
RQ2. Which combination of visual, auditory and olfactory elements provides the highest restorative benefits in hospital healing landscapes?

2. Literature review

2.1 Hospital healing landscape: biophilic design

The biophilia hypothesis suggests that humans have an inherent preference for nature, which positively impacts our well-being and cognitive function. This innate preference for natural environments is closely linked to their restorative potential, as individuals tend to favor settings that promote attention restoration and stress reduction [27]. Building upon this foundation, research in the field of environmental psychology, notably Attention Restoration Theory (ART) by Kaplan & Kaplan [28] and Stress Reduction Theory (SRT) by Ulrich et al. [29], has evolved from various perspectives. Since the 21st century, the biophilia hypothesis has developed into a design philosophy known as biophilic design [27, 30, 31], integrating natural elements into built environments to foster human-nature connections [32, 33]. Unlike traditional design approaches that emphasize functionality or esthetics, the biophilic design approach prioritizes human well-being, incorporating features like greenery, natural light, and water to create visually appealing, psychologically restorative spaces that resonate with our deep-seated environmental preferences [8, 34, 35].

The restorative benefits of biophilic design have been explored in various settings, such as healthcare facilities, residential spaces, commercial establishments, and educational and workplace environments [34, 36, 37]. Among these settings, hospitals present a unique opportunity to leverage biophilic design for therapeutic purposes as they cater to diverse user groups with specific health needs. In hospital environments, biophilic design can be classified into indoor, semi-outdoor, and outdoor spaces, each offering distinct benefits to human health and well-being [37-39]. Indoor spaces often incorporate plants, water features, and natural materials to reduce stress, improve mood, and enhance cognitive function, particularly for patients with Alzheimer's disease and depression [40, 41]. Semi-outdoor areas, such as sheltered gardens, provide a seamless transition between indoor and outdoor spaces, offering therapeutic benefits while ensuring accessibility and comfort [26]. Outdoor environments, including gardens and walking paths, can improve mental health, lower stress levels, and support physical rehabilitation [12, 42].

However, the effectiveness of these spaces is often limited by practical constraints. For instance, indoor and semi-outdoor spaces in hospitals frequently face challenges related to limited space and restricted access to natural elements. While outdoor spaces do provide opportunities for prolonged interaction with nature, they frequently fail to adequately shield users from the pervasive noise of the surrounding environment. In this context, hospital rooftops have emerged as a promising alternative. With their panoramic views and ample spaces, rooftop gardens provide elevated areas that can reduce noise, improve air quality, and promote relaxation [43]. Despite their potential, the restorative effects of rooftop gardens in hospital settings remain underexplored, particularly in terms of physiological and psychological benefits.

To optimize the design and implementation of biophilic elements in hospitals, user assessments play a critical role [44]. Investigations into biophilic design within these healing landscapes underscore the significance of spatial arrangement, varied user needs, the integration of natural elements, and the careful selection of materials and colors [13, 40, 45, 46]. For example, Davis [26] conducted interviews and surveys with hospital staff and patients to assess the advantages and disadvantages of a rooftop garden used for physical therapy. The results revealed that patients were highly satisfied with the garden, while staff members rarely had time to use it. Wood et al. [25] surveyed hospital users in Malaysia, finding their top concerns included emergency safety mechanisms, natural light and ventilation, and water-efficient equipment. In another study, a survey of sick children and hospital staff was conducted using landscape images, and it was found that both groups preferred images featuring child-like characteristics and those with water features [16].

Research has predominantly utilized questionnaires and interviews to explore the post-occupancy effects of hospital healing landscape design and its psychological restorative impacts on users. While these subjective methods provide valuable insights into user satisfaction and perceptions, they are inherently constrained by the participants' selfreported experiences and may not fully capture the complexity of how these environments affect health [47]. For instance, subjective assessments may be influenced by individual biases or social desirability, leading to an overestimation of positive effects or underreporting of negative experiences [48]. Furthermore, such methods cannot accurately measure physiological responses to environmental stimuli, such as increased heart rate or elevated blood pressure, which are crucial for understanding the more objective impacts of healing landscapes [49]. This highlights the need for a comprehensive approach combining physiological and psychological evaluations, which deepens the understanding of how biophilic elements in hospitals contribute to the overall well-being of users.

2.2 Restorative benefits of landscape in multisensory environments

Natural environments offer multisensory experiences, combining rich visual perceptions with auditory cues (e.g., birdsong, rustling leaves, and flowing water) and olfactory stimuli (e.g., plant aromas and earthy scents). In line with this, biophilic design aims to create built environments that engage multiple senses to connect people with nature [32-34]. Currently, the majority of studies on landscape design elements emphasize visual aspects, examining elements such as trees, flowers and groundcovers [50-54]. Studies have shown that plant color, height, and structural composition receive the most attention in visual landscape research, with plant color being the predominant factor in perceived esthetic value [55, 56].

Research on the auditory perception of landscape settings has grown in the last decade, with substantial evidence supporting the benefits of natural sounds [21, 22, 57-63]. For instance, studies have indicated that increasing natural sounds in urban open spaces enhances the pleasantness of urban noise [64, 65]. Some studies have also suggested that the combination of nature-related visual and auditory stimuli offers greater health benefits than visual stimuli alone [23, 66]. However, most studies on auditory perception have focused on public green spaces, traffic areas, residential streets, indoor office spaces, and campuses [67-71], with relatively little focus on the setting of hospital healing landscapes.

Research has demonstrated that olfaction influences mood, memory, behavior, stress, and cognitive performance [24, 72-75]. Some studies have explored the restorative benefits of olfaction in various environments, including healthcare, work, and educational settings [20, 76]. Others have combined olfaction with other senses, such as vision or audition [24, 77-79]. For instance, Ba et al. [24] investigated the interaction between audition and olfaction in the environment and found that positive sensory stimuli enhanced the perception of other senses, while negative sensory stimuli had the opposite effect.

Previous studies have predominantly focused on single or dual sensory modalities—vision, audition, or olfaction [19, 80, 81]. Few studies have explored the integration of three or more senses. Additionally, although hospital healing landscapes are gaining attention and studies have confirmed their positive effects on psychological and physiological health, research on the role of multisensory interactions in these environments remains largely limited. Specifically, there is little research on how different levels of sensory stimuli contribute to varying degrees of restorativeness.

When considering research methodologies for studying multisensory environmental exposure, both traditional laboratory and field research methods have their unique strengths and weaknesses [49, 80]. Laboratory research offers high experimental control but often has low ecological validity [49]. Field research has higher ecological validity but lacks experimental control [82]. Virtual reality (VR) technology combines the strengths of both, offering participants' immersive experience through multisensory interactions, such as visual, auditory, and tactile stimuli [49, 83]. Nevertheless, VR is not without its challenges, including high equipment costs, the inability to fully replicate real-world immersion, and the absence of standardized research methodologies. Despite these challenges, VR remains a highly promising new tool for exploring multisensory environmental exposure.

In light of these considerations, this study aims to bridge the existing research gap by utilizing VR tools and adopting an orthogonal experimental design that combines different levels of visual, olfactory, and auditory sensory elements. By doing so, we seek to determine how design optimization can better support psychological and physiological restorativeness, thus contributing to a deeper understanding of the role of multisensory interactions in hospital healing landscapes.

2.3 Research framework

This study is grounded in two theories developed from the biophilia hypothesis in environmental psychology (Figure 1): Attention Restoration Theory (ART) [84] and Stress Reduction Theory (SRT) [85]. The former is a psycho-functionalist theory, emphasizing mental fatigue, while the latter is a psycho-evolutionary theory, focusing on physiological stress.

ART posits that humans have an innate tendency to respond positively to natural environments and configurations that were favorable for survival during evolution. It encompasses four key concepts: “Being Away,” which refers to the transition from highly focused work into a relatively relaxed environment; “Fascination,” indicating the environment's inherent ability to capture attention naturally; “Scope,” referring to the richness of the restorative environment that stimulates curiosity and the desire for exploration; and “Compatibility,” ensuring that the natural environment aligns with an individual's goals and interests, fostering a sense of belonging and comfort [28, 84, 86]. Furthermore, SRT posits that an evolutionary preference for natural settings triggers positive psychological and physiological responses. It emphasizes that natural landscapes can effectively reduce stress through unconscious and effortless attention attraction. Elements within natural environments, such as greenery and the sound of flowing water, can evoke a state of effortless attention, reducing stress without depleting cognitive resources [4, 29].

These theories complement each other: SRT focuses on physiological arousal and stress-related negative effects, while ART emphasizes mental fatigue recovery, which can be seen as a stress aftereffect that heightens vulnerability to stress [87]. Both theories suggest that environmental preferences are influenced by restoration needs [87], which are closely linked to the restorative potential of an environment. Empirical studies have consistently shown that environments with high restorative qualities (e.g., natural landscapes) are more preferred than those with low restorative qualities (e.g., urban settings) [87-89].

In our research, it is believed that individuals initially perceive restorative landscapes through combined visual, auditory, and olfactory senses. These sensory stimuli can then improve psychological and physiological states by restoring attention and reducing negative stress. Psychological restoration was assessed through two well-established measurements: the Perceived Restorativeness Scale (PRS) tailored to ART, and the State-Trait Anxiety Inventory State (STAI-S) to SRT. Physiological measurements, including Heart Rate (HR), Root Mean Square Successive Difference (RMSSD), Skin Conductance Level (SCL), and Skin Conductance Response (SCR), were monitored as immediate stress indicators [90]. Additionally, environmental preference was measured using the Semantic Differential Scale (SDS), providing complementary insights into the restorative potential of the environments. Different levels of various sensory stimuli can lead to varying degrees of restorative effects [19, 80], providing references for identifying the optimal combination for hospital healing landscape design.

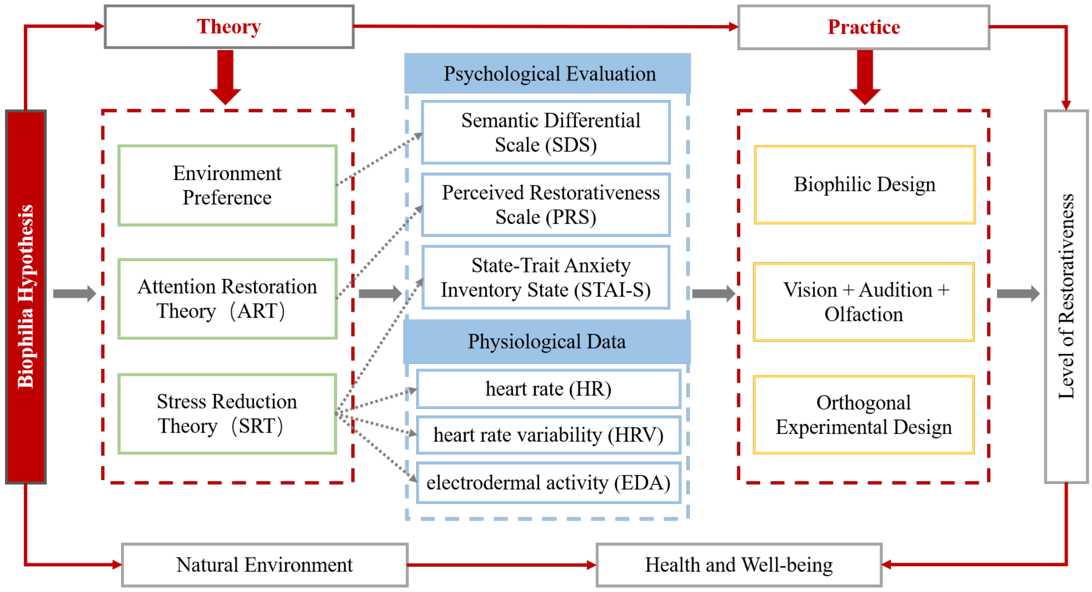


Figure 1 Theoretical Framework.

3. Materials and methods

3.1 Case study

The rooftop garden of Drum Tower Hospital in Nanjing was selected as a case study (Figure 2). Nanjing Drum Tower Hospital is one of the earliest Western medicine hospitals in China and is a large, research-oriented, comprehensive tertiary hospital. It is located in the city center, with excellent transportation access. The hospital's interior and exterior environment designs emphasize harmony between humans and nature, incorporating concepts such as green landscapes and public open space. Unlike conventional healing gardens, this rooftop garden offers a distinct geographical advantage due to its elevated location, which separates it from ground-level traffic and enhances the healing environment for patients.

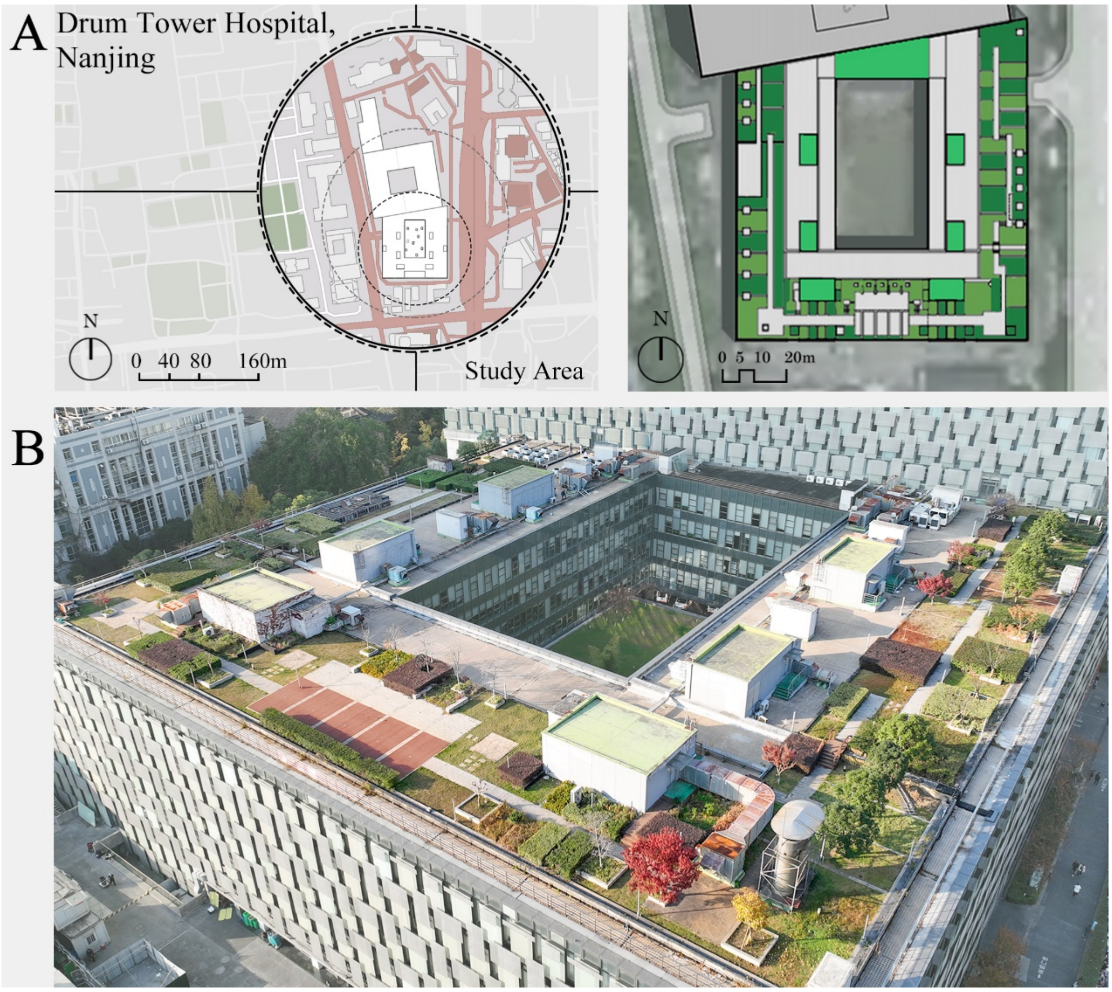


Figure 2 Panel A: Drum Tower Hospital Location Map (left) and Drum Tower Hospital Rooftop Garden Plan (right). Panel B: Photo of Drum Tower Hospital. Source: from the authors.

3.2 Participants

A total of 270 participants were recruited from volunteers in the university library. Participants were recruited on a voluntary basis and received no compensation. The study ensured their anonymity and confidentiality throughout the data collection and analysis. The sample size was determined based on prior research, which suggested that sample size should be at least 30 times the number of independent variables [91, 92]. This approach ensured statistical power to detect differences in the participants' preferences and responses. Participants mainly consisted of undergraduate and graduate students and university staff. Participants were chosen based on the criteria that they were free from visual, olfactory, and auditory impairments, as well as any physiological or psychological conditions, including neurological disorders, chronic illnesses, and cognitive impairments. The socio-demographic information of the participants is presented in Table 1. The gender distribution showed a 1:2 male-to-female ratio. Students accounted for 98.1% of the total, predominantly undergraduates. Furthermore, 98.9% of the participants were aged between 18 and 30 years. Among the participants, 26.7% were landscape architecture majors, and 73.3% were studying non-related fields. Regarding preferences, 48.5% preferred plant landscapes with vibrant color combinations, while 33% favored single-colored expansive lawns. In terms of auditory preferences, 95.9% preferred natural sounds, and 88.9% expressed a positive preference for plant fragrances.

Table 1

Basic Information of Participants

Demographics	Category	Count (percentage)	Demographics	Category	Count (percentage)
Gender	Male	94 (65.2%)	Visual preference	Low plant richness	89 (33%)
	Female	176 (34.8%)		Medium plant richness	50 (18.5%)
Occupation	Student	265 (98.1%)		High plant richness	131 (48.5%)
	Staff	5 (1.9%)			
Age	18-30	267 (98.9%)	Auditory preference	Natural sound	259 (95.9%)
	41-50	2 (0.7%)		Ambient noise in daily life	11 (4.1%)
	31-40	1 (0.4%)		Traffic noise	0 (0%)
Professional in landscape architecture	Yes	72 (26.7%)	Olfactory preference	Single floral scent	215 (79.6%)
	No	198 (73.3%)		Complex floral scent	28 (10.4%)
Experience with VR	Yes	78 (28.9%)		Unscented	27 (10%)
	No	192 (71.1%)			

3.3 Experimental Design

The rooftop garden of Drum Tower Hospital presently exhibits limited plant diversity, characterized by a predominance of evergreen species and a scarcity of flowering plants, while the surrounding auditory environment is largely influenced by traffic noise. Three experimental conditions were designed, representing three levels for each of the following factors: (1) a condition worse than the current environment, (2) a condition identical to the current environment, and (3) a condition better than the current environment. Specifically, the visual factor included low, medium, and high plant richness. The auditory factor comprised traffic noise, ambient noise in daily life, and natural sounds. The olfactory factor ranged from no fragrance to a single floral scent and a complex floral scent. Among these, the current rooftop conditions are represented by medium plant richness, ambient noise from daily life, and a single floral scent.

As this experiment was influenced by three factors with three levels—vision, audition, and olfaction—a total of at least 27 (3^3) experimental groups would need to be tested, with each group being repeated at least 30 times to meet statistical requirements, resulting in a total of 810 experiments. This workload would present a significant challenge. Therefore, an orthogonal experimental design (OED) was used due to its ability to efficiently and economically study multi-factor and multi-level interactions by sampling representative points from the full-scale test [93]. Through this, OED can effectively reduce the number of experimental groups required while maintaining the integrity of the analysis. This approach significantly reduces the number of required experimental groups while preserving the integrity of the analysis. Additionally, OED helps control for potential confounding factors and minimizes experimental error, thereby providing more accurate estimates of the effects of each factor and their interactions [93]. Despite its advantages in reducing causal complexity, few studies have applied OED in experiments related to perceived landscape restorativeness. In this study, using a joint analysis approach in an OED, we grouped various factor levels to create representative experimental groups, resulting in nine experimental groups (Figure 3).

Test Group	Visual Factor	Auditory Factor	Olfactory Factor
1	Level 1 (Low Plant Richness)	Level 1 (Traffic Noise)	Level 1 (Unscented)
2	Level 1 (Low Plant Richness)	Level 2 (Ambient Noise in Daily Life)	Level 2 (Single Floral Scent)
3	Level 1 (Low Plant Richness)	Level 3 (Natural Sound)	Level 3 (Complex Floral Scent)
4	Level 2 (Medium Plant Richness)	Level 1 (Traffic Noise)	Level 3 (Complex Floral Scent)
5	Level 2 (Medium Plant Richness)	Level 2 (Ambient Noise in Daily Life)	Level 2 (Single Floral Scent)
6	Level 2 (Medium Plant Richness)	Level 3 (Natural Sound)	Level 1 (Unscented)
7	Level 3 (High Plant Richness)	Level 1 (Traffic Noise)	Level 2 (Single Floral Scent)
8	Level 3 (High Plant Richness)	Level 2 (Ambient Noise in Daily Life)	Level 1 (Unscented)
9	Level 3 (High Plant Richness)	Level 3 (Natural Sound)	Level 3 (Complex Floral Scent)

Figure 3 Description of Experimental Groups.

The dependent variables included psychological data (State-Trait Anxiety Inventory State, Semantic Differential Scale, and Perceived Restorativeness Scale) and physiological data (Skin Conductance Level, Skin Conductance Response, Heart Rate, and Root Mean Square Successive Difference) (detailed in Sections 3.4.4 and 3.4.5, respectively). The independent variables were visual, auditory, and olfactory factors, each set at three levels. The participants' age, gender, education, occupation, prior VR experience, and preference for different landscape elements were treated as mediating variables, as they were not the primary focus of this study.

3.4 Materials

3.4.1 Visual stimulus materials

Visual stimuli were generated by creating a roof garden scene model using SketchUp. This process involved on-site measurements and photographic references to ensure accurate representation of the environment. After the initial 3D modeling, the scene was imported into Lumion for rendering, where materials and specific vegetation were applied.

The selected plants included dwarf lilyturf tuber (*Ophiopogon japonicus*), carpet sedum (*Sedum lineare*), lavender (*Lavandula angustifolia*), and rose (*Rosa rugosa*). As shown in Figures 3 and 4, the first level of visual stimuli consisted of simple evergreen plants including dwarf lilyturf tuber and carpet sedum. The second level built upon the first by adding roses. The third level enriched the plant diversity by adding lavender in addition to the roses and evergreen plants, resulting in a more layered plant composition. Along the main walkway of the rooftop garden, ten representative waypoints were chosen at approximately 25-meter intervals. At each of these ten waypoints, although the surrounding scenery varied slightly, the plants were arranged in distinct visual groups according to the research design, ensuring that plant diversity was varied among the groups while remaining consistent within each group.

The plants were arranged according to their growing habits, with carpet sedum planted at a density of 20 plants per square meter, dwarf lilyturf tuber at 40 plants per square meter, roses spaced 60 centimeters apart, and lavender spaced 40 centimeters apart in the relevant visual stimuli. A panoramic image was exported from each waypoint and further imported into the 720 Cloud Roaming platform (https://www.720yun.com/u/f88jzruu5u4) to create a panoramic VR walkway (Figure 4). During the testing phase of the walkthrough, the visual fidelity was carefully adjusted and improved to ensure a higher level of realism.

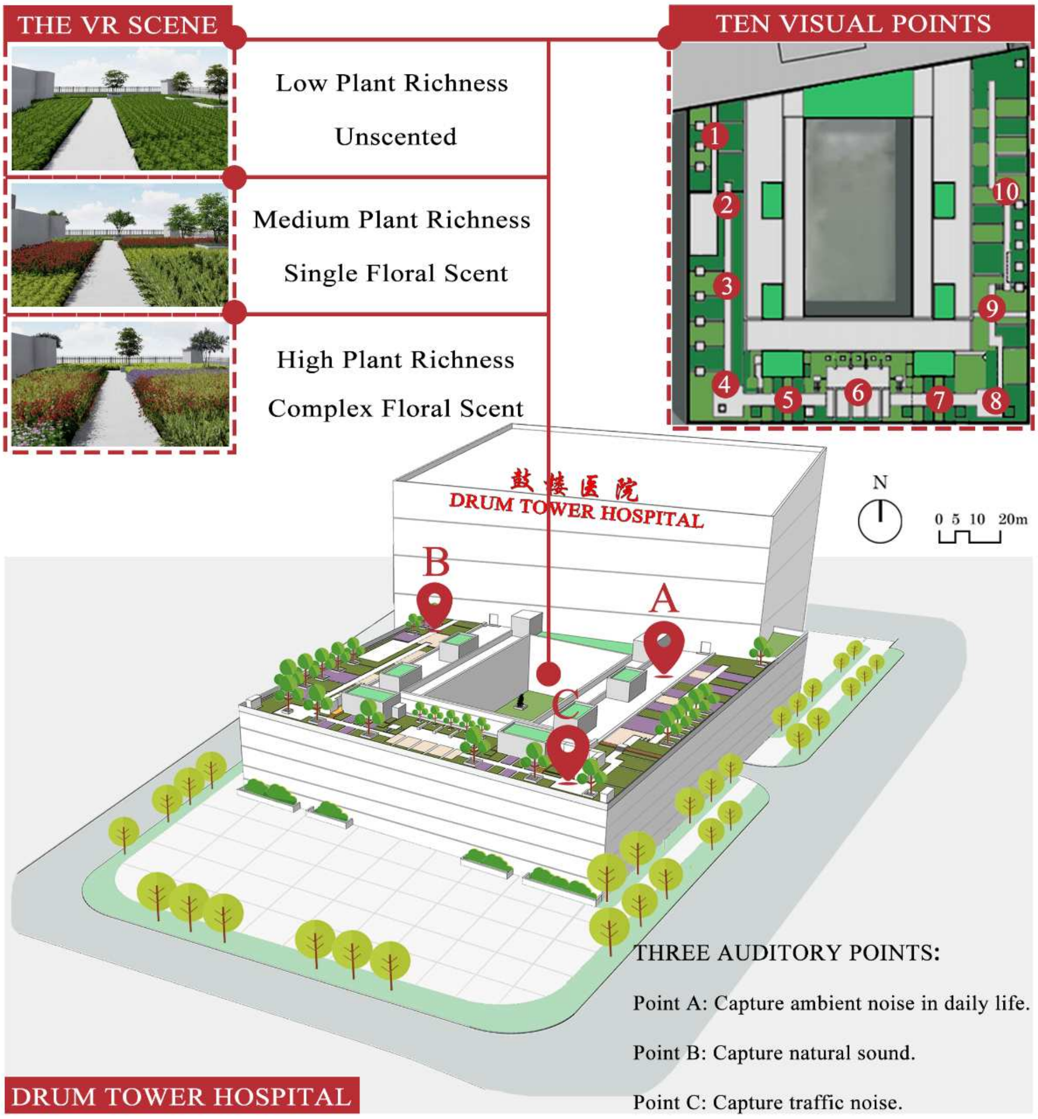


Figure 4 Drum Tower Hospital Roof Garden Visual Point and Auditory Point Selection.

3.4.2 Auditory stimulus materials

Drum Tower Hospital is located in the city center, where surrounding traffic noise is pervasive. Inside the hospital, both living and working sounds are prevalent. Research has shown that natural bird sounds can aid in physiological and psychological recovery [94-96]. Therefore, the auditory materials focused on three main levels of sounds: traffic noise, ambient noise in daily life, and natural sounds [36]. As shown in Figure 4, ambient noise in daily life such as conversations and footsteps were recorded in the hospital atrium (Point A) at an average level of 50 dB(A) [97]. A quieter location (Point B) was chosen to capture natural sounds, primarily birdsong, with an average sound pressure level of 50 dB(A) [98]. Lastly, traffic noise was recorded near the main road (Point C), with an average level of 80 dB(A) [97]. The audio clips were edited to two minutes in Adobe Audition and incorporated into the panoramic images on the 720 Cloud Roaming platform.

3.4.3 Olfactory stimulus materials

The experimental site was predominantly planted with evergreen species, complemented by a few flowering plants. As shown in Figure 3, the olfactory stimuli in the experimental scenarios consisted of three levels. The first level featured no plant-based aromas, while the second level included a single floral scent, using roses as the aromatic plant. The third level combined the fragrances of roses and lavender, creating a complex olfactory environment. Both of these plants are renowned for their essential oils, which are known to help alleviate stress and promote relaxation [99-102]. As shown in Figure 5, Lavender and rose essential oils, provided by Xinjiang Eprhan Spice Co., were selected as olfactory stimuli for this experiment. During the outdoor landscape tour, the odor environment consisted of plant volatile organic compounds mixed with the air.

To maintain experimental feasibility and ensure accurate odor concentration alignment between the laboratory setting and outdoor landscape environments, olfactory stimuli were standardized at a constant level. This approach was implemented despite the inherent dynamic nature of olfactory experiences that typically vary with participant location. The standardized concentration was determined through precise calculations based on simulated plant volatile dispersion patterns within a controlled spatial environment [103]. As shown in Figure 5, in the designated boxed area, lavender is cultivated across approximately 23.7 square meters. The concentration of aromatic compounds in this lavender essential oil was simulated to establish the appropriate concentration ratio for use in olfactory stimulation materials.

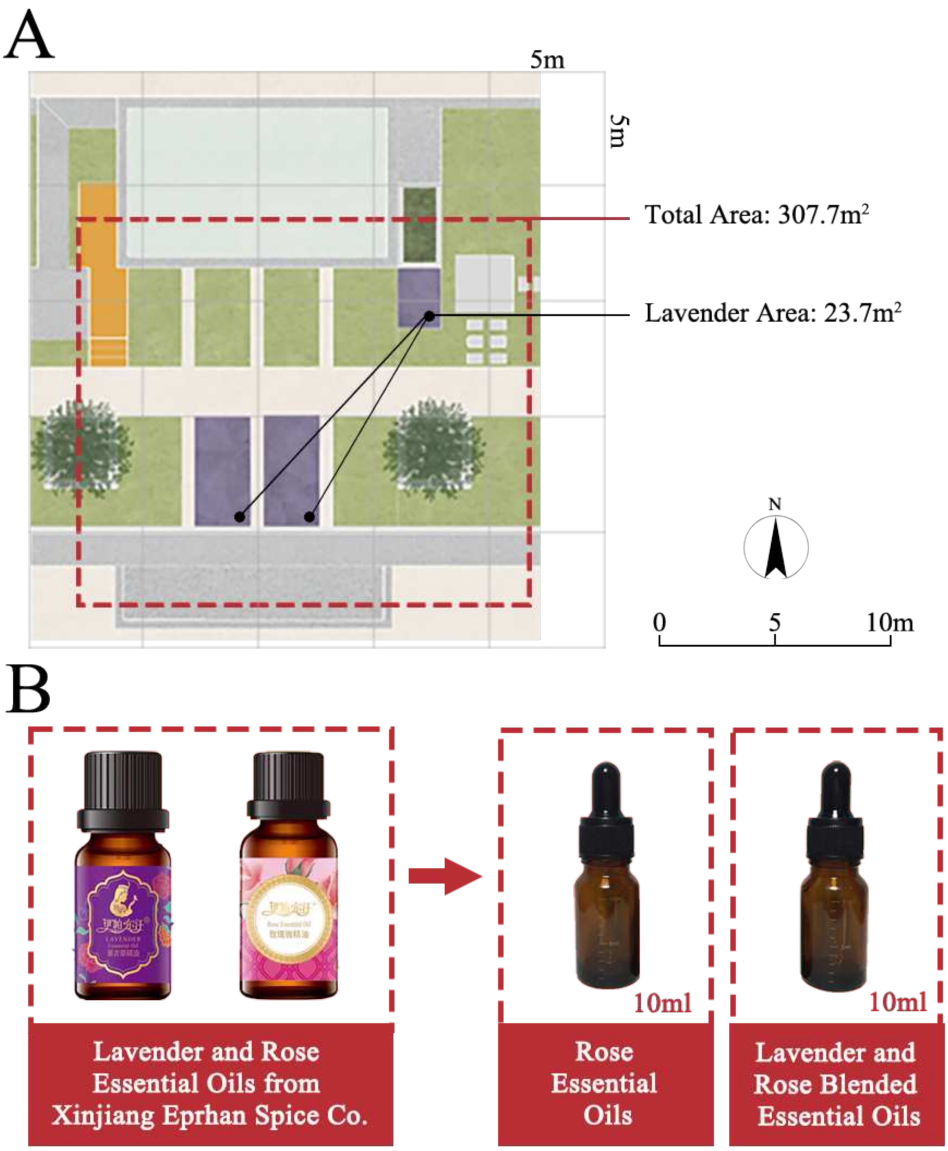


Figure 5 Panel A: Partial Area Plan of the Roof Top Garden. Panel B: Physical Images of Essential Oil Materials. Source: from the authors.

The primary characteristic aromatic compounds in the air of the selected area are linalool and linalyl acetate [104]. The selected area covers approximately 307.7 square meters, with an assumed space height of 2.7 meters, resulting in a volume of approximately 830.8 cubic meters. The concentrations of the main characteristic aroma compounds were obtained from an essential oil test report provided by Xinjiang Eprhan Spice Co:

$$\text{Linalool} + \text{Linalyl acetate} = 29.37\ \text{ng/L} + 31.16\ \text{ng/L} = 60.53\ \text{ng/L}$$

$$60.53 \text{ ng/L} = 0.06053 \text{ mg/m3} \approx 0.061 \text{ mg/m3}$$

Assuming that plant volatiles flow in the selected space, the amount of lavender essential oil required for the experiment was calculated as follows:

$$0.061 \text{ mg/m}^3 \times 830.8 \text{ m}^3 \approx 50.7 \text{ mg} \approx 0.05 \text{ g}$$

The number of essential oil drops was calculated as

$$\text{Drops of Essential Oil} = \text{Volume} \times \text{Concentration} \times 20 \text{ Drops}$$

$$1\text{ml} = 20 \text{ drops}$$

Therefore, the number of essential oil drops that matched the lavender odor concentration at the site was

$$10 \text{ ml} \times (0.05 \text{ g} / 10 \text{ ml}) \times 20 \text{ drops} = 1 \text{ drop.}$$

Similarly, the amount of rose essential oil was calculated. The primary compounds responsible for the fragrance of rose essential oil are geraniol, citronellol, and β-Phenylethanol. The amount of essential oil required was calculated as follows:

$$0.981 \text{ ug/L} = 0.981 \text{ mg/m}^3$$

$$0.981 \text{ mg/m}^3 \times 830.8 \text{ m}^3 = 815.0148 \text{ mg} \approx 0.815 \text{ g}$$

$$10 \text{ ml} \times (0.815 \text{ g} / 10 \text{ ml}) \times 20 \text{ drops} = 16.3 \text{ drops} \approx 16 \text{ drops}$$

The essential oils were stored in a brown glass bottle at -18°C to protect them from light. During the experiment, the container was opened, and a drop of essential oil was placed on a scent test strip. The strip was then presented to the participants at 3 cm from the nasal cavity, with the scent released at a controlled frequency to ensure that the subject could perceive the odor.

3.4.4 Measurement of psychological data

The State-Trait Anxiety Inventory State (STAI-S), the Semantic Differential Scale (SDS), and the Perceived Restorativeness Scale (PRS) were used as indicators for a subjective evaluation of environmental restorative effects (Figure 6). To assess stress levels, the participants first completed a stress test, inducing levels of anxiety or heightened stress. Additionally, the STAI-S was administered to quantify stress levels [105-108]. The STAI-S consists of 10 items, divided into 5 positive and 5 negative wordings. Each item was rated on a scale from -2 to 2, with the corresponding intensity levels of "Not at all," "Somewhat," "Moderate," "Quite a lot," and "Very much." [19, 109, 110].

This study employed the SDS [106, 111, 112] to assess public environmental preferences regarding hospital healing landscapes across three sensory modalities: vision, audition, and olfaction. Environmental preference refers to an individual's inclination toward a specific environment, which in turn influences their behavior. It is also considered an important indicator of the restorative effects of the environment [113]. The SDS consists of a series of bipolar adjective pairs, each divided into five equal rating levels, and the scores for each dimension range from -2 to 2 [113, 114]. By selecting a position on the scale, respondents indicate their understanding and feelings toward the item being measured. A questionnaire was developed based on three sensory factors, with each factor evaluated through five criteria. For visual factors, the criteria included comfort, ambiance, attractiveness, harmony, and the appropriateness of other sensory environments [113]. For auditory factors, the criteria encompassed pleasantness, rhythm, interest, ambiance, and the appropriateness of other sensory environments [23, 115]. For olfactory factors, the criteria focused on pungency, comfort, refreshing, preference, and the appropriateness of other sensory environments (Figure 6) [116].

Based on previous research [117, 118], the Chinese version of the PRS was used for a subjective evaluation of environmental restorative quality. For each of the four dimensions of restorative experience — being away, fascination, consistency, and compatibility—three, five, three, and four items were selected, respectively (Figure 6). A five-point Likert scale was applied, with the subjects rating each item on a scale from -2 ("very non-compatible") to 2 ("very compatible") [119, 120].

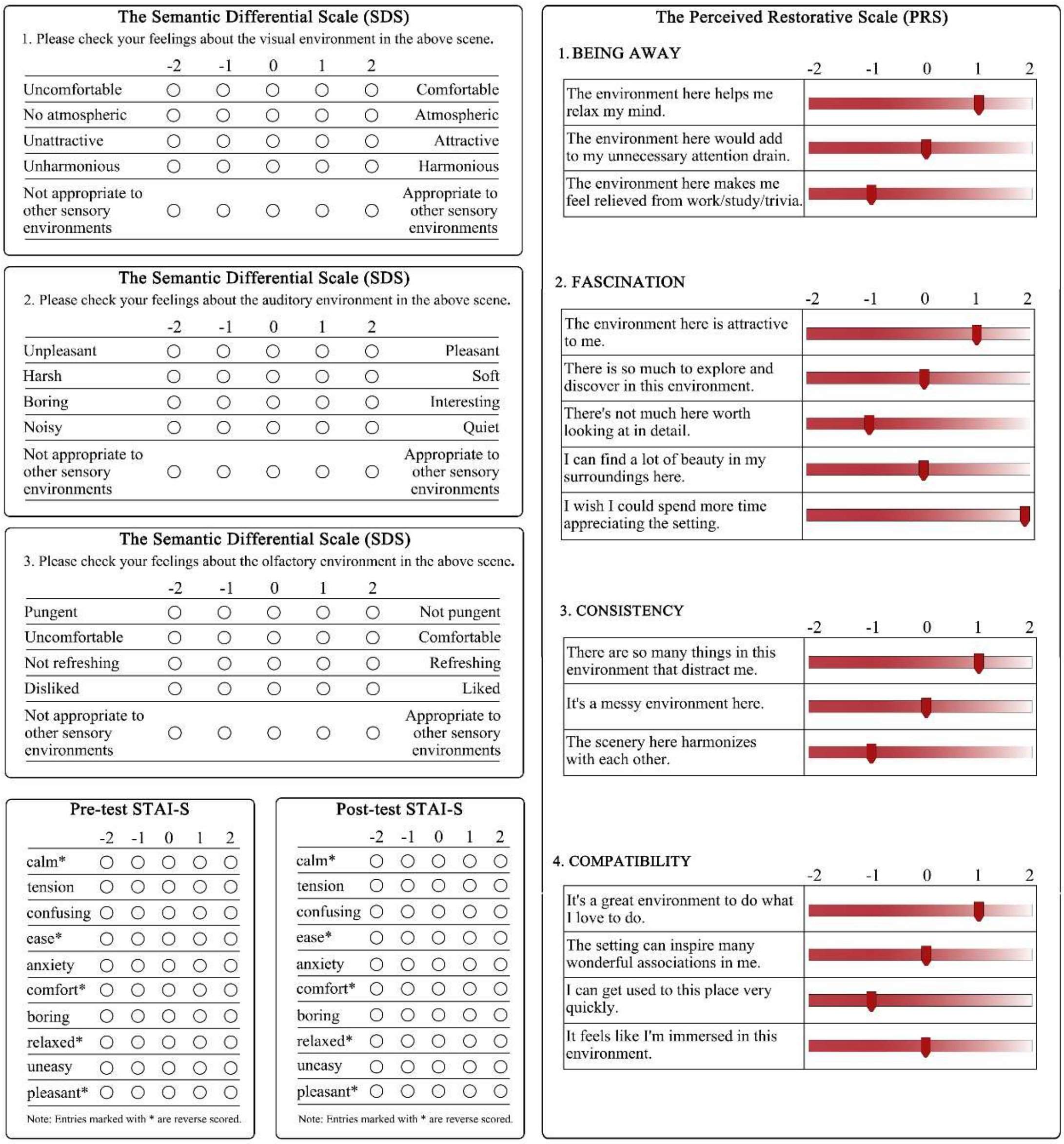


Figure 6 Psychological Scale.

3.4.5 Measurement of physiological data

Skin Conductance Level (SCL), Skin Conductance Response (SCR), Heart Rate (HR), and Root Mean Square Successive Difference (RMSSD) were selected as physiological indices. The restorativeness of hospital healing landscapes was primarily evaluated based on electrodermal activity (EDA) and heart rate signals [121, 122]. Electrodermal activity (EDA), also known as galvanic skin response (GSR), is measured using two metrics: SCR and SCL. A higher SCR indicates a stronger emotional response to the stimulus, such as fear or surprise, while a lower SCR reflects a weaker response or a more stable mood [70]. Heart rate signals were analyzed using two metrics: HR and RMSSD. The RMSSD, a time-domain measure of heart period variability, is an important indicator of heart rate variability (HRV) [123, 124]. When emotions are low, the RMSSD value decreases, and conversely, it increases when emotions improve [125].

Psychological data were collected using multimodal perception equipment provided by the PsychTech Company (https://kycloud.psychtech.cn/index). The hardware included the multimodal Myin perception terminal (PTES100) and the edge computing terminal (PTEC100). The software comprised the Multimodal Wristband Collector App and the Research Cloud Platform (Figure 7). The PTES100, an electrodermal wristband, monitors skin conductance and heart rate data. The PTEC100 receives raw data, processes them, and computes relevant features before transmitting the data to the Research Cloud Platform. In signal processing, window length and step length are crucial parameters for feature extraction. For HR and RMSSD signals, a 20-second window with a 4-second step length was used to capture stable cardiovascular features while maintaining computational efficiency. For SCR and SCL signals, an 8-second window with a 2-second step length allowed for more accurate detection of rapid emotional responses. The values of these signals were recorded automatically in the Research Cloud Platform, and the mean values were calculated using statistical analysis after the experiment.

3.5 Procedure

3.5.1 Overview

The research was approved by the ethics committee of the authors' institution. A total of 270 participants were randomly and equally assigned to one of the nine groups, as shown in Figure 3. Before the experiment, the participants were informed of the research purpose and procedures, and they provided written consent by signing an information sheet and consent form. After completing the basic information form, the participants underwent a 2-minute stress test involving math problems, followed by the

STAI-S. During this period, EDA and HR were continuously monitored using a wearable device. The participants then wore VR headsets to experience the healing landscape corresponding to their assigned group. Afterward, they completed the STAI-S again, followed by the SDS and the PRS.

3.5.2 Experimental setting

The VR experiment was conducted in the seminar room of the XXXX university library (masked for peer review), which was quiet without noise interference or special odor. The room was maintained at a constant temperature of 25℃, with the windows and doors closed throughout the experiment. At the end of the experiment, the room was ventilated for 10 minutes by opening the windows and doors.

The participants sat quietly in front of a round table in the seminar room (Figure 7). The equipment for the experiment was placed on the table, including Pico Neo3 VR glasses, the PTES100, the PTEC100, sealed plant oils, test strips, and questionnaires (including basic information, the STAI-S, the SDS, and the PRS). The experiment was conducted from April 17 to May 16, 2024, with the subjects participating daily from 9:00 AM to 12:00 PM and from 2:00 PM to 6:00 PM.

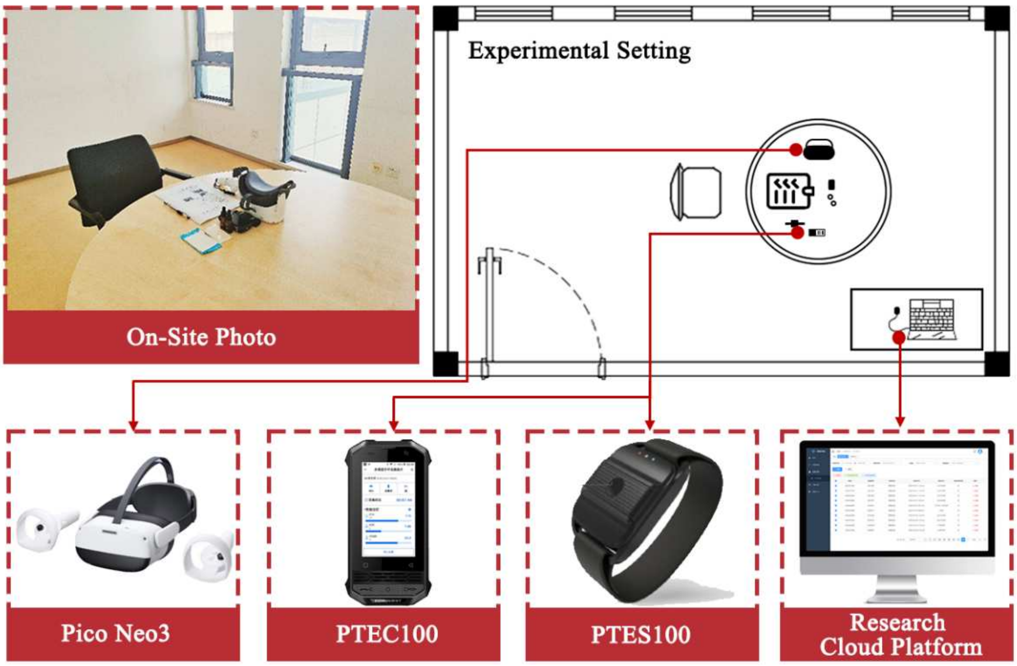


Figure 7 Experimental setting.

3.5.3 Experimental procedure

The experiment comprised six main steps: pre-test instruction, pre-test questionnaire, stress test, pre-stimulation STAI-S, stimulation, and post-stimulation STAI-S, SDS, and PRS (Figure 8).

(1) Pre-Test Instruction: Upon arrival in the seminar room, the experimenter provided an overview of the experiment and outlined the necessary precautions.

(2) Pre-Test Questionnaire: The experimenter first cleaned the participant's left wrist with non-alcoholic wipes. While the arm dried, the participant completed the basic information form. The experimenter then applied the bracelet to the participant, who remained still for 2 minutes in preparation for the stress test.

(3) Stress Test: The participant was asked to complete 100 math problems within a 2-minute time limit, during which the multimodal bracelet collected data.

(4) Pre-Stimulation STAI-S: Immediately after the stress test, the participant completed the STAI-S.

(5) Stimulation: The participant was exposed to scene stimuli corresponding to their experimental group. Olfactory stimuli were presented to the groups with an olfactory intervention using test strips with specific essential oils. Physiological data were collected in real time during this phase.

(6) Post-Stimulation STAI-S, SDS, and PRS: After the experiment, the participants removed the VR glasses and bracelet, and then they completed the STAI-S, SDS, and PRS based on their true feelings, thus concluding the experiment.

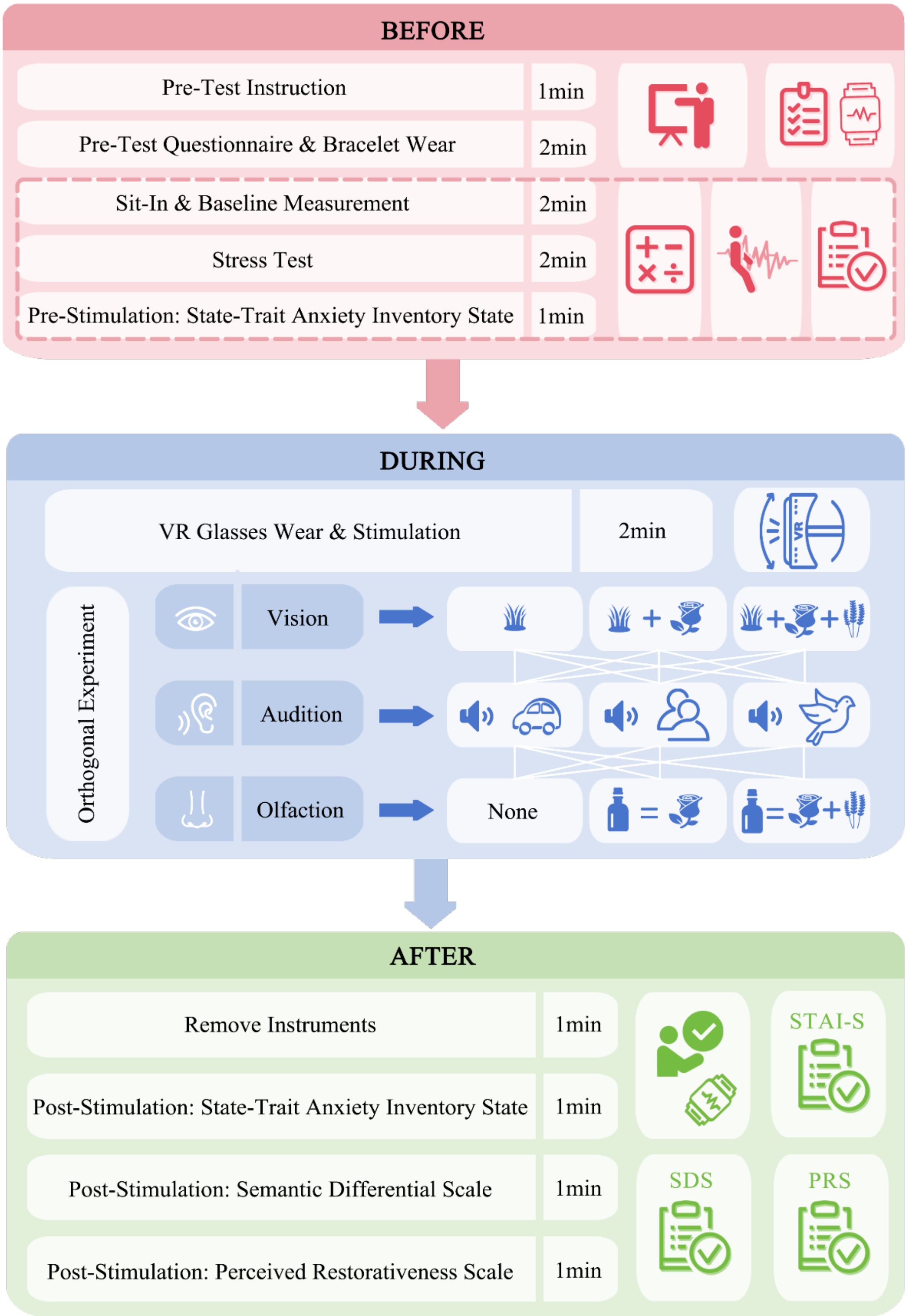


Figure 8 The Experimental Procedure.

3.6 Data analysis

A total of 270 valid data sets were collected after statistical verification. A data analysis was conducted using EXCEL and SPSS 27.0 software. A descriptive analysis was performed on the socio-demographic information obtained from the pre-test questionnaire.

The participants completed the STAI-S immediately after the stress phase and again at the end of the relaxation phase. The difference between the scores of these two phases was calculated; a positive difference indicates effective anxiety reduction [107, 108]. Following the relaxation phase, the participants completed the SDS and PRS, with higher total scores indicating better relaxation effects [111, 112, 118, 120].

To account for individual differences in skin conductance, the primary index used was the difference between SCL during the recovery phase (SCLr) and the stress phase (SCLs). The difference between SCL during the pressure and VR phases was calculated for each group, as shown in the following equation:

$$SCL = SCLr - SCLs$$

Similarly, the mean differences in SCR, HR, and RMSSD were calculated. Smaller SCL, SCR, and HR values (positive numerical values) indicate a more relaxed and calm mood for the participants, while a larger RMSSD value corresponds to greater relaxation. Therefore, a smaller difference value in SCL, SCR, and HR suggests better recovery, while a larger difference value in RMSSD indicates a more effective recovery [55, 124].

The orthogonal experimental design was implemented to efficiently identify key influencing factors and determine optimal sensory combinations while minimizing experimental trials. Range analysis was selected over ANOVA and regression techniques for analyzing psychological and physiological data due to four key advantages [126]: First, its computational efficiency and straightforward interpretation enable rapid identification of factor significance, proving particularly valuable for practical applications [127]. Second, the method demonstrates superior performance with small sample sizes—a crucial advantage for orthogonal experiments that inherently involve limited experimental runs [128]. Third, its robustness against outliers ensures reliable results, especially given our dataset's non-uniform distribution and presence of extreme values [129, 130]. Fourth, the approach provides direct optimization insights by clearly identifying optimal factor-level combinations [128].

The key indices of a range analysis output include the K value, average K values (K avg), range (R), and optimal level. The K value represents the sum of the physiological and psychological indices at each level of each factor [93]. The K avg is the average of the K values for a specific factor level, calculated by dividing the K value by the number of experiments at that level. The R value is the difference between the maximum and minimum average K values of each factor, representing the variation in the experimental data caused by the factor. A higher R-value indicates a greater impact of the factor on the corresponding indicator [93].

The restorative effects vary with different physiological indicators. For example, for RMSSD, larger values correspond to better recovery, as the difference in RMSSD values is positive. Therefore, the range (R) for RMSSD is calculated as follows:

$$\text{Range (R)} = \text{K avg}_{(max)} - \text{K avg}_{(min)}.$$

Conversely, for SCL, SCR, and HR, smaller values indicate better recovery effects. Therefore, the range (R) for these indices is calculated as follows:

$$\text{Range (R)} = \text{K avg}_{(min)} - \text{K avg}_{(max)}.$$

However, for all data indicators, the larger the R value, the greater the influence of the factor. Finally, the optimal level of a factor is the level that maximizes or minimizes the response variable (depending on the goal of the experiment). The effects of various combinations of visual, auditory, and olfactory factors on physiological measures (e.g., RMSSD, SCL, SCR, and HR) and psychological measures were compared. This comparison aimed to identify the optimal combination level, which corresponds to the OED design as in Figure 3.

4. Results

4.1 Psychological data results

4.1.1 STAI-S analysis

The sum of the scores from the stimulation phase was subtracted from the sum of the scores from the stress test phase, and the results for all nine groups were found to consist of positive numbers (Table 2). This indicates that, for each of the nine experimental groups, the VR-based healing landscape environments effectively reduced the participants' anxiety to varying degrees. These findings suggest that exposure to the VR landscape had a restorative effect, demonstrating its potential for alleviating state anxiety.

Table 2
Difference analysis of STAI-S

Group	Pre-Test STAI-S	Post-Test STAI-S	Difference STAI-S
1	-3	6	9
2	-1	8	9
3	-2	14	16
4	0	10	10
5	-1	11	12
6	0	10	10
7	-1	11	12
8	-1	9	10
9	2	13	11

4.1.2 SDS analysis

The SDS was developed based on environmental preference for three sensory factors: auditory, visual, and olfactory, and structured around five dimensions. The sum score for all SDS dimensions were calculated, and a range analysis was conducted (Table 3). A comparison of the factor levels revealed that the olfactory factor had the greatest effect, showing the highest extreme deviation (R = 9.6), while the visual factor had the least impact (R = 3.07) (Figure 9). An analysis of the average K-values (K avg) for each factor level, presented in the polar plot, indicated that the third level of the olfactory factor had the greatest impact (K avg = 13.43). The optimal levels for both the visual and auditory factors were also found to be at the third level (Figure 9).

When looking at the scores for vision, audition and olfaction separately, participant perceptions for each specific measure are detailed in Figure 10. In terms of visual perception, environments with low, medium and high plant diversity all showed positive values across all five dimensions, with high plant diversity having the highest total score (M = 5.30), followed by medium plant diversity environments (M = 3.43), and low plant diversity. Regarding auditory perception, traffic noise was rated negatively in “pleasantness,” “rhythm,” “interest,” “ambiance,” and “appropriateness”, with the lowest total score (M = -2.36). In contrast, natural bird song had the highest score (M = 6.41), while ambient noise in daily life scored moderately (M = 0.91). In olfactory perception, odorless environments showed negative values for the “refreshing” dimension, with a total value of 1.02. Conversely, environments with plant fragrances scored positively across all five dimensions. Composite plant fragrances having the highest average score (M = 5.51) and single-plant fragrances second (M = 5.18).

Table 3
Range analysis results in SDS

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	23.13	16.2	11.5
	2	26.86	27.43	30.53
	3	32.33	38.69	40.29
K avg	1	7.71	5.4	3.83
	2	8.95	9.14	10.18
	3	10.78	12.9	13.43
Optimal level		3	3	3
R		3.07	7.5	9.6
Number of levels		3	3	3
Number of replicates per level r		3	3	3

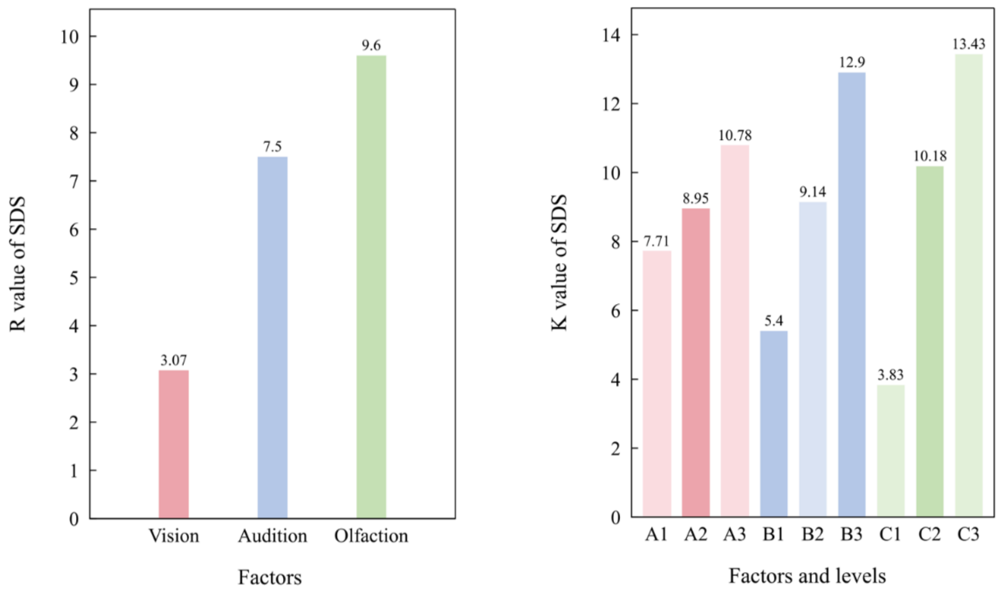


Figure 9 Comparison of factors for R value of SDS (left) and Comparison of K value of SDS for each factor at each level (right).

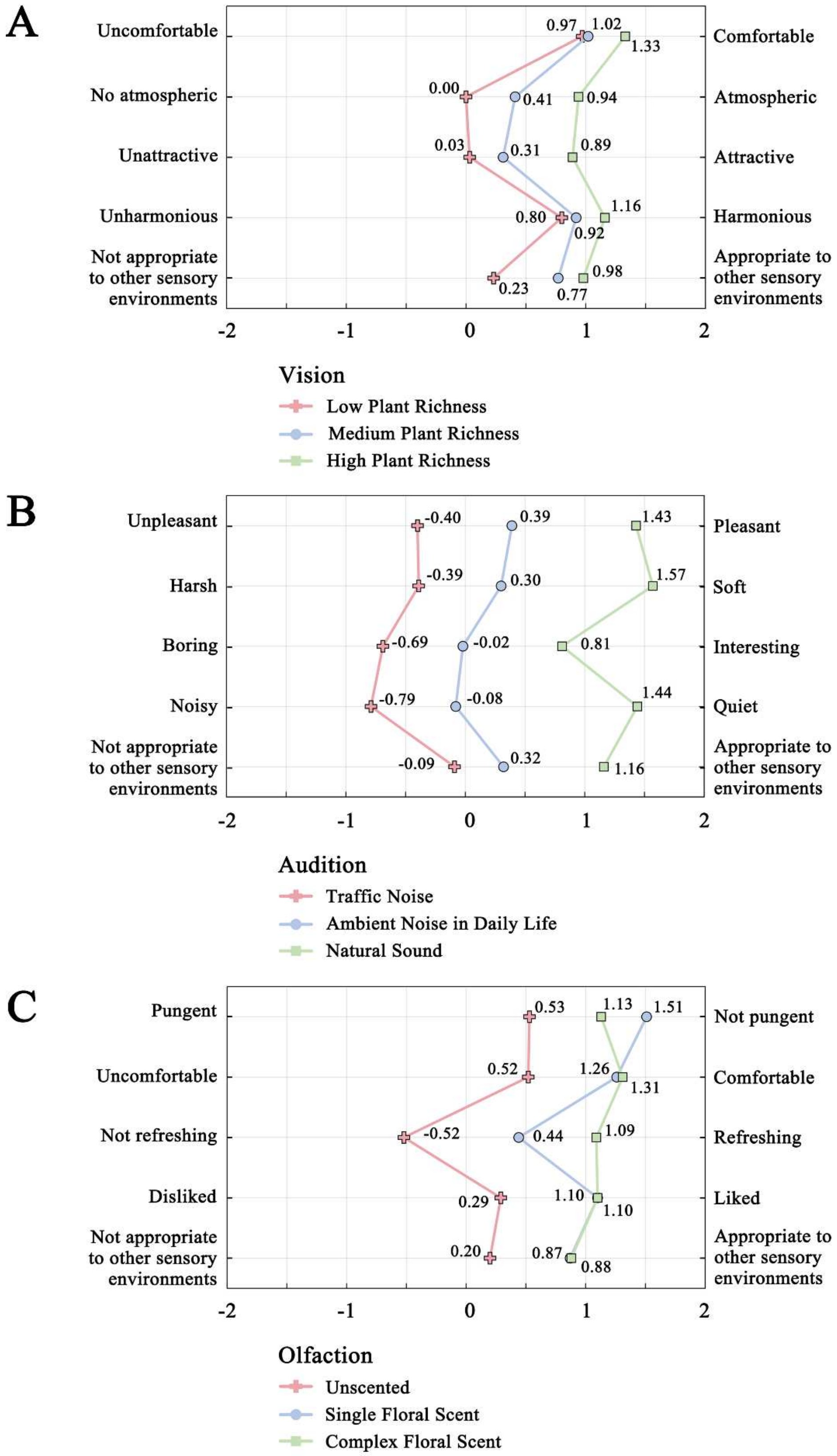


Figure 10 Panel A: Semantic Differential Scale for Visual Factor. Panel B: Semantic Differential Scale for Auditory Factor. Panel C: Semantic Differential Scale for Olfactory Factor.

4.1.3 PRS analysis

The PRS typically contains four main dimensions: being away, fascination, consistency, and compatibility. The scores of all subjects were summarized, and a composite mean score for each restorative dimension was calculated and analyzed for extreme variance (Table 4). It was found that the visual factor had the greatest influence, having a higher extreme variance value than the other factors (R=5.39). The olfaction factor had the least influence (R=3.97) and could be further optimized as a secondary factor in subsequent designs (Figure 11). The average K-values (K avg) for each factor level, analyzed through the polar plot, showed that the third level of the visual factor had the greatest impact (K avg = 8.8). Similarly, the optimal levels for both the auditory and olfactory factors were also at the third level (Figure 11).

Table 4
Range analysis results in PRS

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	10.23	10.27	9.63
	2	14.93	18.59	20.4
	3	26.4	22.7	21.53
K avg	1	3.41	3.42	3.21
	2	4.98	6.2	6.8
	3	8.8	7.57	7.18
Optimal level		3	3	3
R		5.39	4.14	3.97
Number of levels		3	3	3
Number of replicates per level r		3	3	3

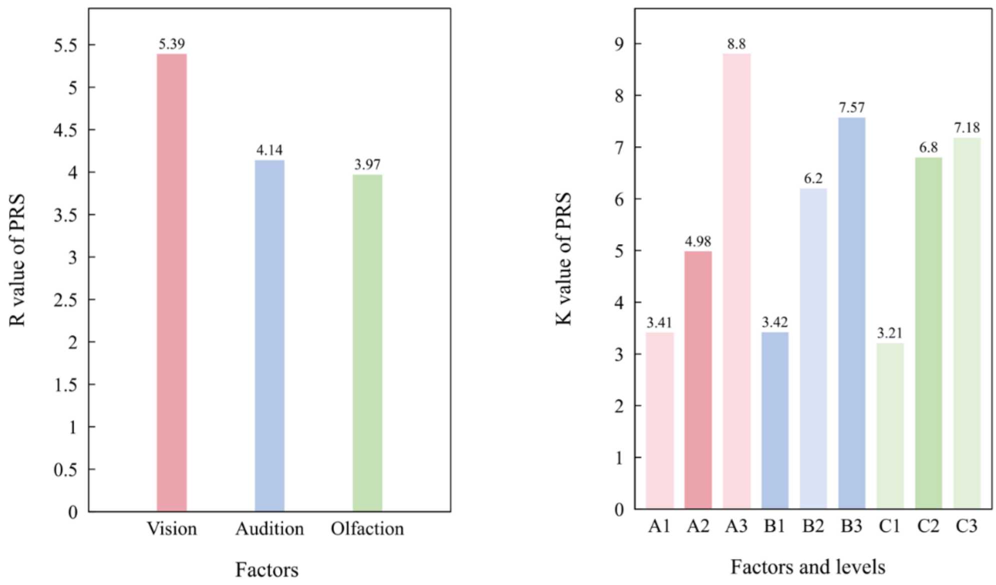


Figure 11 Comparison of factors for R value of PRS (left) and Comparison of K value of PRS for each factor at each level (right)

4.2 Physiological data results

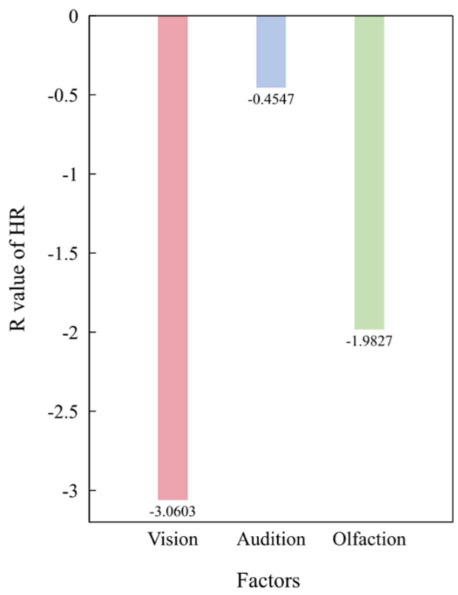
4.2.1 HRV analysis（HR and RMSSD）

A higher HR typically reflects increased sympathetic activity in the autonomic nervous system, often associated with stress or tension. The difference in the mean HR between the stress and relaxation phases was calculated and analyzed for extreme differences (Table 5). The auditory factor had the greatest effect, with the highest extreme difference value (R = -0.4547), while the visual factor had the least effect (R = -3.0603) (Figure 12). An analysis of the average K-values (K avg) for each factor level through the polar plot revealed that the third level of the auditory factor, with the greatest impact, was optimal (K avg = -1.965). The optimal level for both the visual and olfactory factors was also the third level (Figure 12).

Table 5
Range analysis results in HR

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	-0.356	-4.531	-5.05

	2	-5.237	-4.704	-2.066
	3	-9.537	-5.895	-8.014
	1	-0.1187	-1.5103	-1.6833
K avg	2	-1.7457	-1.568	-0.6887
	3	-3.179	-1.965	-2.6713
Optimal level		3	3	3
R		-3.0603	-0.4547	-1.9827
Number of levels		3	3	3
Number of replicates per level r		3	3	3



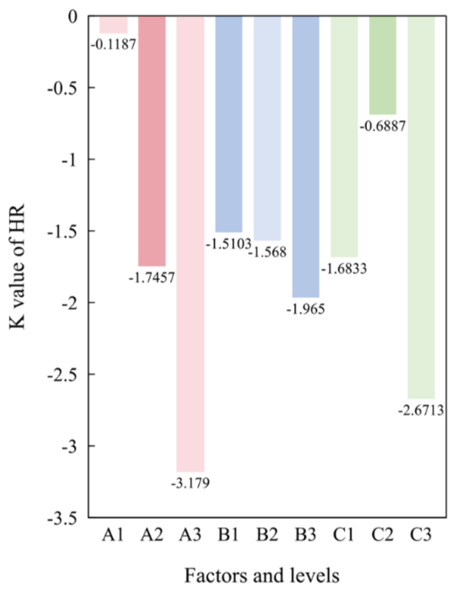


Figure 12 Comparison of factors for R value of HR (left) and Comparison of K value of HR for each factor at each level (right)

A higher RMSSD indicates stronger parasympathetic activity, typically reflecting a more relaxed state. The mean RMSSD difference between the stress and relaxation phases of the experiments was calculated and analyzed for extreme differences (Table 6). The auditory factor had the greatest effect, with the highest extreme difference value (R = 7.096), while the olfactory factor had the smallest effect (R = 1.5243) and could be further optimized as a secondary factor in future designs (Figure 13). An analysis of the average K-values (K avg) for each factor level through the polar plot revealed that the third level of the auditory factor, with the greatest impact, was optimal (K avg = 4.267). The optimal level for both the visual and olfactory factors was also the third level (Figure 13).

Table 6
Range analysis results in RMSSD

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	1.797	-8.487	0.532
	2	-2.539	5.635	4.312
	3	10.691	12.801	5.105
K avg	1	0.599	-2.829	0.1773
	2	-0.8463	1.8783	1.4373
	3	3.5637	4.267	1.7017
Optimal level		3	3	3
R		4.41	7.096	1.5243
Number of levels		3	3	3
Number of replicates per level r		3	3	3

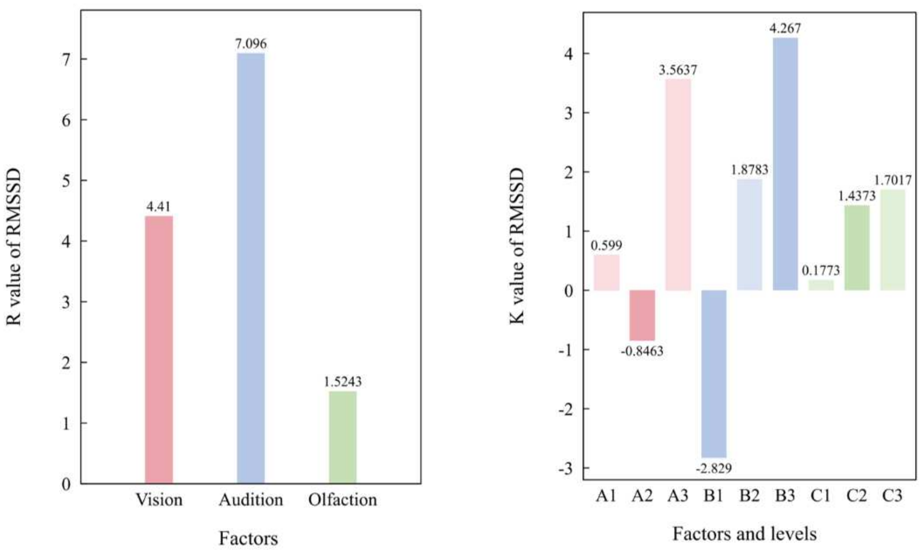


Figure 13 Comparison of factors for R value of RMSSD (left) and Comparison of K value of RMSSD for each factor at each level (right)

4.2.2 EDA analysis (SCL and SCR)

The mean SCL difference between the stress and relaxation phases was calculated and analyzed for extreme variance (Table 7). Based on the plots comparing the factor levels, the auditory factor had the greatest effect, with the highest extreme difference value (R = -0.0177). The visual factor had the smallest effect (R = -0.0203). An analysis of the

K avg for each factor level through the polar plot revealed that the third level of the auditory factor, which had the greatest impact, was optimal (K avg = 0.122). The optimal level for both the visual and olfactory factors was also the third level (Figure 14).

The mean SCR difference between the stress and relaxation phases was calculated and analyzed for extreme variance (Table 8). The olfactory factor had the greatest influence, although its extreme values were similar to those of the other factors (R = -0.0017). The audition factor had the least effect (R=-0.011) and was almost similar to the visual factor (R=-0.0073) (Figure 14). An analysis of the K avg for each factor level through the polar plot revealed that the third level of the olfactory factor, which had the greatest impact, was optimal (K avg = 0.001). The third level was also optimal for both the visual factor (K avg = -0.0017) and the auditory factor (K avg = -0.003) (Figure 14).

Table 7
Range analysis results in SCL

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	0.375	0.419	0.41
	2	0.427	0.383	0.415
	3	0.366	0.366	0.343
K avg	1	0.125	0.1397	0.1367
	2	0.1423	0.1277	0.1383
	3	0.122	0.122	0.1143
Optimal level		3	3	3
R		-0.0203	-0.0177	-0.024
Number of levels		3	3	3
Number of replicates per level r		3	3	3

Table 8
Range analysis results in SCR

Item	Level	Factor 1	Factor 2	Factor 3
		Vision	Audition	Olfaction
K	1	0.017	0.024	0.008
	2	0.005	0.002	0.006
	3	-0.005	-0.009	0.003
K avg	1	0.0057	0.008	0.0027
	2	0.0017	0.0007	0.002
	3	-0.0017	-0.003	0.001
Optimal level		3	3	3
R		-0.0073	-0.011	-0.0017
Number of levels		3	3	3
Number of replicates per level r		3	3	3

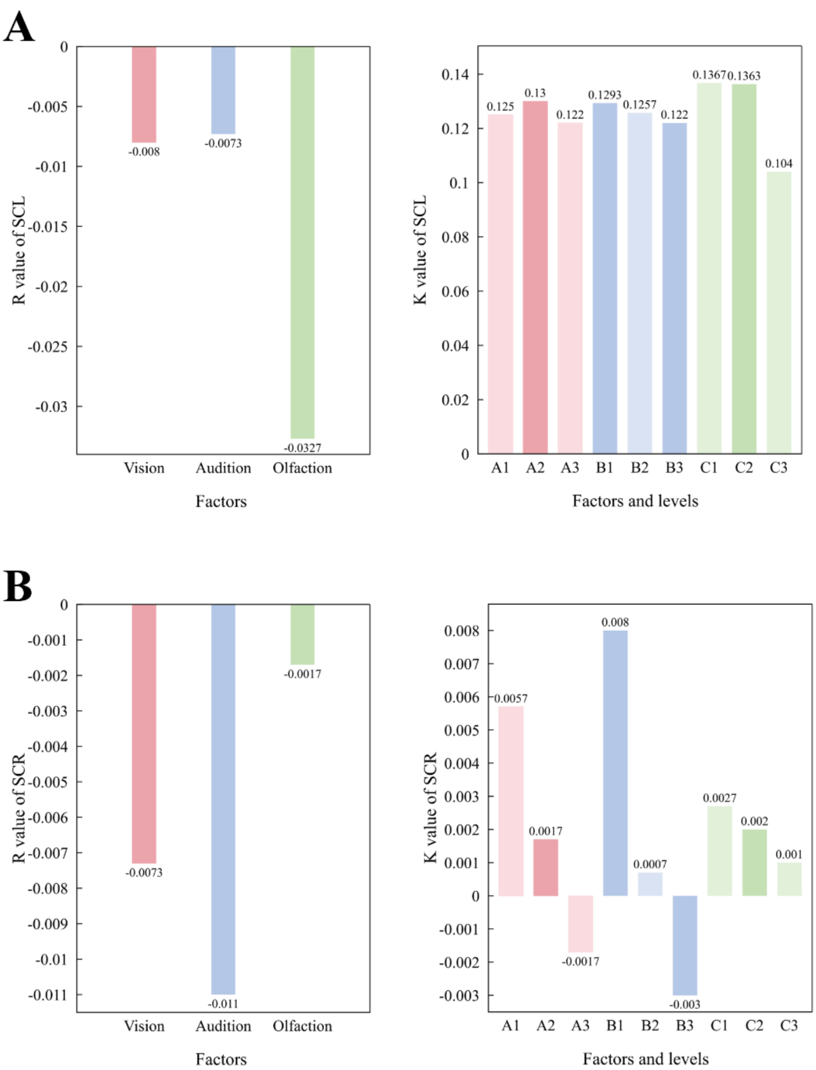


Figure 14 Panel A: Comparison of factors for R value of SCL (left) and Comparison of K value of SCL for each factor at each level (right). Panel B: Comparison of factors for R value of SCR (left) and Comparison of K value of SCR for each factor at each level (right).

5. Discussion

5.1 The effect of different sensory elements on the restorative benefits of hospital healing landscapes

In relation to the psychological data, the mean difference in the STAI-S scores across all nine experimental groups was a positive number, indicating that exposure to multisensory hospital healing landscapes helps to alleviate stress and reduce anxiety. This is in line with previous studies showing that exposure to natural environments can improve mental well-being [109, 110]. Interestingly, within the experimental groups, even groups characterized by low plant richness, traffic noise, and neutral odor demonstrated a notable reduction in stress levels. Given that traffic noise is typically perceived as a negative environmental factor [61], the inclusion of visual elements may have played a compensatory role, alleviating its adverse effects.

The SDS results showed that the olfactory factor had the greatest influence compared to vision and audition. Previous studies have shown that public preference is positively correlated with an environments' restorative potential [51]. In the pre-test questionnaire, participants exhibited diverse olfactory preferences, some favored a floral-free environment, while others disliked overly strong complex floral scents. This variability in preferences likely contributed to the higher R-value for the olfactory factor. In contrast, the smaller R-value for the visual and auditory factors in SDS results reflects the more consistent preferences of the participants, as most favored a rich plant landscape and natural sound, resulting in less variation in the data for these two factors [51, 131].

In individual SDS measurements, participants rated higher scores in environments with high plant richness, natural bird sounds, and complex floral scents. Specifically, in the visual environment, higher plant richness correlated with increased scale scores, indicating that participants experienced stronger environmental preferences.

Conversely, the auditory environment with traffic noise received negative scores, reflecting discomfort and negative emotions associated with such noise [61, 76]. In the olfactory environment, the presence of plant fragrance yielded higher scores compared to a no-scent environment, with complex floral scents achieving the highest scores. This suggests that the participants felt more relaxed in such environments.

Regarding PRS, visual factors typically have a greater impact on PRS results compared to the other two stimuli. This is presumably due to the fact that vision stands as one of the most prominent senses in human perception, exerting direct emotional and cognitive influences [28, 132]. Another reason may be that visual stimuli often enhance the overall restorative impact in multisensory environments, further reinforcing their dominant role in perceptual recovery [19].

In terms of the physiological data, the R-value indicates that the auditory stimuli had the most pronounced effects, as evidenced by HR, RMSSD, and SCL. During the stress phase, HR significantly increased. During the stimulation phase, it began to decrease, while RMSSD exhibited the opposite trend. Natural sounds, particularly those incorporating bird sounds, were associated with a reduction in heart rate. This is consistent with previous studies indicating that nature sounds help to reduce physiological stress markers [133]. In contrast, environmental noise dominated by traffic has been shown to elevate stress levels, further underscoring the significance of integrating natural sounds into healing landscapes. The robust response to auditory stimuli underscores the pivotal role of auditory factors in facilitating physiological relaxation and stress recovery [24, 134].

Furthermore, the SCR data suggests that the olfactory stimuli had the greatest impact on this physiological marker. This aligns with previous studies showing that scents such as lavender and rose can directly influence the autonomic nervous system, thus promoting relaxation and reducing stress [99-101].

5.2 Optimal combination of visual, auditory, and olfactory elements in hospital healing landscapes

Psychologically, environments with the visual, auditory, and olfactory senses at the third level—such as birdsong, rich plant diversity and complex plant aromas—led to the highest restorative effects. These findings align with previous research indicating that exposure to natural elements such as abundant vegetation and birdsong can significantly reduce stress and enhance mood [52, 53, 56]. Additionally, studies have shown that natural fragrances from plants, such as lavender, jasmine, and rose, positively impact mental health [79, 100, 101, 135].

This study extends these findings by integrating visual, auditory, and olfactory stimuli, identifying the optimal combination of rich plant diversity, natural birdsong, and complex plant aromas for the most restorative effects. Such environments are likely to evoke feelings of tranquility, attention restoration, and a sense of connectedness with nature, which is especially advantageous in urban areas where natural spaces may be scarce [70, 96, 136].

The physiological data further support these findings, with HR, RMSSD, and EDA reflecting the greatest restorative effects in the presence of a high plant abundance, birdsong, and complex plant aromas. Our results align with those of previous studies showing that exposure to natural sounds and diverse plant life can lower stress markers, including HR and cortisol levels [96, 97, 137]. In particular, natural soundscapes have been shown to promote autonomic balance, as indicated by increased HRV and reduced sympathetic nervous system activity [70, 133]. Likewise, the scents of plants have been shown to activate the parasympathetic nervous system, facilitating relaxation [99-101].

The alignment of psychological and physiological responses in this study underscores the value of integrating multisensory elements into healing landscape design in healthcare settings. Incorporating diverse plants, bird sounds, and aromatic flavor can create restorative environments, offering a holistic approach to enhancing mental well-being in hospitals and similar facilities. These findings support the biophilic design movement, which advocates for incorporating natural elements into built environments to improve human health and well-being.

5.3 Theoretical contributions and practical implications

This research enhances the comprehension of Attention Restoration Theory (ART) and Stress Reduction Theory (SRT) by introducing a multisensory dimension that combining visual, auditory, and olfactory elements to explore the restorative benefits of hospital healing landscapes. While previous research has predominantly focused on visual stimuli, this study highlights the role of auditory and olfactory stimuli in fostering restoration. By systematically investigating the relative contributions of different sensory stimuli to multiple restorative indices across physiological and psychological aspects, this research reveals the synergistic effects of high plant diversity, natural bird sounds, and complex floral scents in maximizing restorative outcomes. The use of an orthogonal experimental design provides a robust methodological framework for future sensory and perceptual studies, deepening the understanding of how multisensory environments impact human health and well-being.

This study provides actionable design guidelines for architects and landscape designers, emphasizing the integration of rich plant colors, diverse nature sounds, and plant aromas to enhance the healing potential of hospital landscapes. These guidelines inform the design of outdoor, semi-outdoor, and indoor spaces within healthcare facilities, focusing on optimizing patient recovery through intentional sensory experiences. For outdoor spaces, incorporating a variety of brightly colored and seasonally varying plants stimulates visual senses, while natural sounds (e.g., bird songs and water features) and aromatic plants (e.g., lavender and rosemary) create a tranquil and restorative environment. For semi-outdoor spaces, partially enclosed structures can introduce natural light and scenery, complemented by artistic installations and natural soundscapes to create a private yet accessible healing atmosphere. For indoor spaces, despite spatial constraints, an oasis can be created through thoughtfully selected plants, vertical greenery, and floral arrangements, enhanced by soft music and essential oil diffusers.

Additionally, the government should support the inclusion of healing landscape concepts in hospital design by developing relevant standards and encouraging healthcare institutions to pursue green building certifications (e.g., LEED) and ecological restoration-based solutions. Public awareness campaigns and funding initiatives can also play a crucial role in advancing the adoption of healing landscapes, ultimately contributing to the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 11 (Sustainable Cities and Communities).

6. Conclusion

Multisensory landscape stimuli have the potential to improve well-being. However, traditional research has primarily concentrated on one or two sensory modalities in hospital healing landscape design, overlooking the synergistic effects of visual, auditory, and olfactory stimuli. Building on ART and SRT, this study explores the synergistic effects of visual, auditory, and olfactory stimuli on the restorative potentials of hospital healing landscapes. The combination of physiological and psychological data suggests that the restorative benefits of healing landscapes are most effectively realized in environments rich in plant color diversity, complemented by nature sounds and complex plant aromas. The results provide implications for sustainable landscape design in healthcare settings.

This study has several limitations: First, the participant sample was predominantly composed of university students and staff in laboratory environments, limiting the generalizability of findings. Future research should include more diverse participants across age groups, occupations, and cultural backgrounds in real-world settings [138]. Second, the analysis was constrained by the data distribution and sample size, precluding statistical significance testing. Subsequent research could employ advanced analytical techniques, such as ANOVA and regression analysis, to strengthen the statistical validity. Third, the two-minute exposure duration may be insufficient for capturing complete restorative effects and could compromise the temporal accuracy of electrodermal activity due to its inherent response latency [55]. Future studies should consider extending exposure periods and incorporating multimodal physiological monitoring, including high-resolution galvanic skin response sensors, brain activity tracking, eye-tracking, and cognitive performance assessments. Fourth, the study's focus on a limited number of plant species in a single site may restrict the applicability of the findings to other plant varieties. Expanding the range of plant species and site scenarios in future research could enhance ecological validity. Finally, this study primarily focused on the impact of vision, olfaction, and audition; however, future research could expand to include the investigation of thermal, tactile, and other perceptions in restorative experiences. While olfactory and auditory stimuli were maintained at constant levels for experimental control, implementing a spatially adaptive model that dynamically adjusts sensory inputs based on participant location holds the potential to significantly enhance environmental fidelity and immersion.

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