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Exploring the creation of multi-modal soundscapes in the indoor environment: a study of stimulus modality and scene type affecting physiological recovery

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ABSTRACT

Currently, soundscapes in outdoor environments have been well researched, but there is still a lot of research to be done on the application of soundscapes in indoor environments and their corresponding audiovisual elements. In this study, we used a combination of experiments and questionnaires to obtain physiological metrics and subjective ratings for three stimulation modalities and six soundscape scenes, explored the effects of stimulus modality and scene type on human physiological recovery, and compared the relationships between different physiological metrics and fatigue, attention, and arousal. It is hoped that this will provide a basis for soundscape creation in indoor environments. The results showed that audiovisual stimuli enabled participants to better maintain attention and moderate arousal. A single visual stimulus reduced participants' resistance to the scene. Forest, ocean, and starry sky scenes were more in line with participants' preferences and presented physiological data consistent with subjective ratings. Multi-sensory creates connections between more physiological indicators, and strong connections between the various indicators of the Electrocardiograph can serve as an important basis for feedback on changes in the body. There was a strong link between the effects of scenes on participants and cognitive experience. We make the following conclusion: it is possible to combine different stimulus modalities for the interior space of the building, and to choose a restorative scene as the main soundscape. The findings can provide a reliable database for constructing comfortable indoor environments.

1. Introduction

As an important part of the human living space, the soundscape has a subtle influence on both the physiological and psychological aspects of human beings [1][2]. ISO 12913-1 states that the soundscape is defined as "the acoustic environment that is perceived or experienced and/or understood by a person or persons in context" [3]. A series of studies have been conducted to show that soundscapes can influence our emotions and sensory experiences [4], and that calming soundscapes can promote recovery from stress-induced physiological changes [5]. Herzog found that natural environments were more effective for psychological recovery after presenting natural and artificial environments to two groups of subjects through photographs, videos, and field walks [6]. Compared to urban environments, natural environments positively impact physiology, and psychology, and promote human recovery. [7][8]. This includes effects such as attention recovery and stress reduction [9][10]. Noise pollution in the current environment is harmful to the human body and can lead to a variety of health problems [11], including depression, anxiety, and insomnia on the psychological side, and tinnitus, heart disease, and cognitive dysfunction on the physical side [12]. However, there are few related objective interpretations and specific soundscape content studies. Therefore, the correlation between soundscape and the recovery of human physiological indicators and the preference for different types of soundscapes are important research directions.

It has been found that different types of soundscape, different sound sources, and locations affect individuals' evaluations of their audiovisual experience [13][14], and it is hoped that questionnaires will be standardized to assess people's perceptions of sound preferences [15]. Noise in the environment also affects participant evaluations [16].

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Due to the large subjective cognitive factors of soundscape, corresponding social research methods and psychological research methods are involved in many evaluation systems. Yong found that soundscape perception is mainly influenced by acoustic comfort, visual images, and spatial openness [17]. Characteristics of the soundscape, including loudness, frequency, preference, and auditory satisfaction, influence the perception of soundscape aesthetics [18]. Indrani investigated the effects of situational factors, personal characteristics, and demographic factors related to space use on psychological states, expectations, soundscape perception, and work behaviors [19][20]. The sound semantic approach is also often used as an important method in the assessment of indoor soundscapes [21], where the semantic approach is used to express people's emotional responses to soundscapes by describing and quantifying sound features. Residents' perceptions of park soundscapes differed significantly in terms of loudness [22], pitch, and sense of belonging, but the perceived differences in timbre, coverage, and distance from the sound source were relatively small.

Soundscapes are the relationship between people (subject) and environmental space (element). People directly obtain environmental information through their senses of hearing and sight. These objectively existing sounds and landscapes work together with pre-existing experiences to influence human emotions. This process involves behavioral cognition, physiological instincts, neurotransmission, and many other subject areas. However, the subjective perception of soundscapes belongs to real human perceptual responses [23]. Traditional soundscape evaluation studies are often conducted through participants' subjective representations and questionnaires, interviews, and dialogues [24][25]. In recent years, measurements from physiological indicators have also been developed to study human perception of soundscapes and the recovery effects induced by soundscape stimuli can also be reflected by objective data on the changes in physiological indicators [26]. When choosing physiological indicators, those that are easily accessible and sensitive to changes are usually chosen first, such as electroencephalogram [27][28], electromyography, heart rate variability [29], and respiratory rate [30][31]. Neurophysiological studies have emphasized the important influence of personal characteristics and emotional responses on the quality of soundscape recovery. Multichannel EEG studies human emotions and relaxation states by showing changes in EEG waveforms [32]. In addition, eye-movement indicators show the change of mood, with participants in positive moods having more gaze points, number of dwells, and dwell times [33]. The study found that the efficiency of visual processing means that less cognitive effort is required to process visual information, which in turn promotes the restoration of attention [34]. The effects of stimulus-induced physiological and psychological recovery were proportional to trends in mean blink length, number of gaze points, and number of sweeps. Smaller pupil diameters and more gaze points indicate better psychological recovery from the environment [35]. Physiological indicators can objectively show the changes in the state of body and mind.

The three elements of the soundscape are people, sound, and environment. Visual-auditory is the main sense of soundscape perception. Visual stimulation and auditory stimulation are important ways to promote restoration and relaxation of the human body. Studies have shown that soundscapes have a more significant effect on psychological recovery than single auditory [36] and single visual stimuli [37][38]. Human perception of environmental soundscapes is influenced by sounds, images, and related interactive behaviors [39]. The visual perception of trees in natural environments has been found to have an important restorative effect on physical and mental relaxation [40]. Since auditory cognitive processes are very brief, auditory stimuli can prompt emotional changes in a very short period, thus inducing corresponding physiological responses. Liu found that the visual environment and the visual-auditory environment have better effects on acute recovery [41]. However, the auditory interventions may produce the most significant stress recovery effect over a longer recovery time. For elderly people, auditory elements in the residential environment had a more significant effect on psychophysical recovery and were more effective in promoting psychological relaxation and physiological recovery [42]. Different listening times also affect the subjects' judgment and perception of the acoustic environment, with unsuitable duration leading to discriminative perceptual biases and sensory adaptation [43]. It has been found that the strongest response to sound is within 1 minute, and it has been hypothesized that a stimulus duration of 1 minute provides the best recovery [29].

Soundscape types are closely related to the recovery of people's soundscape experience. The soundscape itself consists of landscape and sound. Depending on the location, they can be categorized into natural soundscapes and urban soundscapes [44]. According to the source of the soundscape elements, it can be divided into natural soundscape and artificial soundscape [45]. It can also be categorized into single soundscape and composite soundscape based on whether there is consistency of elements in the soundscape. In addition, soundscapes are often categorized into four types: geophysical, biological, human, and mechanical sounds [46]. There are also studies that categorize the sounds of human activity as a type of soundscape [7], such as footsteps and fireworks. Scholars have also used subjective semantic descriptions and acoustic attributes to categorize and differentiate soundscapes in their studies [47]. The aim of this study is to investigate the use of a single soundscape in indoor environments and is therefore categorized as a natural

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soundscape and a man-made soundscape, with the difference being whether or not the production or combination of the elements requires a secondary artificial treatment. Naturally occurring audiovisual elements that can be directly derived from them are considered natural soundscapes, whereas soundscapes that require human involvement to synthesize any audiovisual elements are classified as man-made soundscapes. This classification supports the diversity of soundscape design and provides guidance for optimizing current inner-city spaces.

Different areas create different soundscapes, and the resulting differences also affect human perceptual discrepancy, with urban soundscapes being closer to current daily life compared to natural soundscapes [26]. Natural soundscapes usually include forests [48][49], water bodies, oceans [50], grasslands [51], deserts [52], mountains, etc. Zhang explored the effects of architectural soundscapes on human emotions by using three sound types (street music, traffic sounds, and fountain sounds) as variables [14]. In the natural environment, the desert, as a special ecological environment, produces a soundscape with a certain uniqueness [53], and the desert soundscape specifically includes wind, sand flow, and insect sounds. But there are fewer studies related to it. Extraordinary landscapes have been found to evoke deeper emotional and cognitive responses [54], and to promote psychological and physiological improvements through feelings of awe [55]. Starry sky meets this criterion, and it is often associated with emotions such as serenity, mystery, and romance in the visual aspect. In terms of sound, research has found that music can improve human mood [56], and improve sleep quality, promote brain function recovery [57]. Alpha brainwave sound is essentially specific audio obtained through processing, such as binaural beats, and white noise. Through specific frequency (8 ~ 12 HZ) or psychological effect, it indirectly prompts the brain to enter the dominant state of alpha brainwave [58]. The brain's "synchronization effect" adjusts to the reduced levels of stress hormones, making people feel comfortable and safe. Therefore, the man-made soundscape obtained by combining it with the starry sky scene provides a certain reference for the subsequent design of man-made soundscape for indoor environments. In addition, the restorative benefits of more extraordinary landscapes (glaciers, volcanoes) and other man-made sounds could be explored.

The aim of this study was to provide reliable evidence for designing indoor soundscapes to improve physiological recovery of residents. Therefore, the study addresses the following two main questions: (1) Which of the three stimulation modalities had the most significant effect on the participant's recovery? How do physiological data change during recovery? (2) Which type of soundscape is more likely to facilitate participants' psychological and physiological recovery? Whether subjects would have preferred these soundscapes? (3) What is the relationship between physiological indicators and subjective evaluation? What correlations exist between physiological indicators?

2. Methods

This study utilized a combination of subjective and objective methods. The body's state of recovery was assessed by recording physiological data. The participants recorded physiological data under different stimulus modalities and scene types through the corresponding physiological data equipment. In addition, subjective questionnaires filled in by participants after completing the experiments were statistically analyzed to further explore the relationship between the stimulus modality, scene type, and physiological recovery.

2.1. Participants

The experimental subjects selected for this study were recruited from a group of young people over the age of 20. We issued a notice of recruiting subjects through online channels, and finally selected 20 eligible participants according to the specific requirements of the experiment, with an average age of 23.25 (standard deviation = 1.372; minimum = 20; maximum = 25), of which 10 were males and 10 were females. Previous studies dealing with the perception of audiovisual stimuli have used similar numbers of participants for experiments [37][59][60]. Due to the large number of stimuli, a longer period of time was required. To ensure that subjects completed the experiment under the same conditions as much as possible, adequate rest periods were therefore ensured between stimulus modalities. The subjects were required to be well-rested before the experiment, thus ensuring a good mental state and concentration during the experiment. The order of stimulus materials was determined according to a drawing lot to avoid experimental inaccuracies caused by a single order. All participants in this experiment read and signed the consent form before participating in the experiment and were paid a certain amount of money for the experiment at the end of the experiment.

2.2. Experimental design

2.2.1. Experimental variables

The variables of the experiments in this study included two dimensions of stimulus modality and scene type, and the stimulus modalities included 3 types, audiovisual, visual, and auditory. Audiovisual stimulus modality is the

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complete soundscape. Scene types included forest, ocean, grassland, desert, starry sky, and urban, totaling 6 scenes. The stimulus modalities were then numbered (A-audiovisual, B-visual, C-auditory), and the six scene types were sorted in the order of 1 ~ 6, totaling 18 tasks.

2.2.2. Experimental equipment

This experiment mainly collects physiological data, EEG data, and eye movement data, and the data collection equipment is as follows:

(1) ErgoLAB Wearable Wireless Physiological Recording Module: Specifically, it includes the measurement of electrocardiographic activity (EDA), respiratory signals (RESP), electrocardiographic signals (ECG), and skin temperature (SKT). The electrodes of the EDA measurements are located in the palm of the hand, while the electrodes of the other data measurements are located in the center of the frontal thoracic cavity and were secured to the chest with an elastic chest strap.

(2) ErgoLAB wearable wireless EEG measurement system: specifically, 16-lead semi-dry electrode measurements, mainly selecting 16 channel recording electrodes in the frontal pole (Fpz), frontal lobe area (F7, F3, Fz, F4, F8), central area (C3, Cz, C4), parietal lobe area (P7, P3, Pz, P4, P8) and occipital lobe area (O1, O2). The electrodes were connected according to the international standard protocol 10-20 electrode placement system.

(3) Eye movement equipment: a set of desktop Tobii eye-tracker produced by Tobii, Sweden, with a sampling frequency of 50 Hz and a gaze localization accuracy of 0.5, was used to record eye movements using its system. The ErgoLAB human-computer platform was paired and integrated with the Tobii Studio software for displaying the experimental simulations and collecting experimental data.

2.2.3. Physiological indicators

Physiological indicators (heart rate variability, respiratory rhythm, brainwaves, eye movements) are closely related to fatigue state, attention, and mood changes in humans [61]. Responses are made through the autonomic nervous system, which consists of two main branches: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Activation of the SNS is usually associated with the body's state of arousal and alertness, while activation of the PNS promotes relaxation [62]. Together, these two maintain the body's sympatho-vagal balance. Heart rate variability (HRV) provides an objective and reliable assessment of autonomic nervous system activity. Due to the short duration of our electrocardiographic signals (ECGs), RMSSD [41] and PNN50 were mainly chosen [63]. Under time constraints and emotional stress, SNS activity increases and heart rate variability (HRV) decreases overall. Cardiac Inter beat Interval (IBI) can reflect autonomic function and self-regulation [64], and can also indicate attention and cognitive resource allocation [65]. When the human body is in a state of stress and emergency, the heart rate (HR) increases and the IBI decreases within the normal range, which represents that the whole is tense and alert [66], and the attention and cognitive resources are more focused, and these two indexes can indicate the subject's arousal level and stress level. The frequency-domain metrics were chosen to be the high-frequency power (HF) and the low-high-frequency power ratios (LF/HF) in the HRV power spectrum. LF reflects SNS activity, HF reflects PNS activity [67]. When participants relax, HF rises and LF/HF falls. In addition, studies have shown that changes in skin conductance level (SCL) and skin conductance response (SCR) are related to an individual's level of arousal. When the body tends to calm down, the SNS activity decreases, the skin temperature (SKT) decreases, the sweat secretion decreases, and the resistance value increases. Respiratory rhythm is also correlated with its level of relaxation [68]. Respiratory frequency (RF) decreases and respiratory depth (RD) increases when the body relaxes.

β waves in brain waves represent the brain's arousal and are generally more pronounced when a person is attentively focused or tense. Higher levels of β waves have been found to be stimulating and awakening. θ waves are related to cognitive load and are more pronounced when in a state of fatigue. It usually occurs when you are about to fall asleep. This slower brainwave causes you to show a more relaxed and open mind. α waves are between β and θ and represent mild relaxation, and wakefulness but calmness. θ/β (TBR) has been noted in studies as an electrophysiological marker of attentional control [69], and a lower TBR should indicate a greater allocation of attention to that stimulus [70]. $(\alpha + \theta)/\beta$ is defined as the fatigue factor R. The higher the R-value, the higher the fatigue [71]. Pupil change is an unconscious reflex. Changes in pupil size are controlled by the smooth muscles in the iris; the SNS causes the dilator muscle to contract, resulting in an increase in pupil size, while the PNS causes the sphincter muscle to contract, resulting in a decrease in pupil size. When a person is in a relaxed state, the pupil diameter decreases, indicating a reduced level of arousal and psychological load, and the body tends to calm down in a restorative phase [72]. Pupil dilation indicates that the subject is concentrating, while a decrease in pupil diameter can also indicate that the subject

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is fatigued. Based on existing studies, we believe that a decrease in HR, LF/HF, RF, and R-value and an increase in RMSSD, PNN50, HF, and RD can be considered as stimulus-induced relaxation. TBR and mean pupil diameter were also used to determine changes in subjects' attention, arousal, and fatigue levels.

2.2.4. Subjective assessment

In this experiment, a five-level Likert preference scale was designed for the stimulus modality and scene type, which was scored after the subjects completed each type of stimulus, with higher scores representing higher preferences of the participants [73]. The subjective questionnaire scale used for audiovisual stimuli was the Perceived Restorative Soundscape Scale (PRSS) [36]. The scale was developed by Hartig [74] based on the four basic characteristics of restorative environments proposed by Kaplan and his wife and was later adapted to form a complete restorative scale. The scale consists of six dimensions (Fascination, Being-Away-To, Being-Away-From, Compatibility, Coherency, and Scope). When exposed to each stimulus, subjects scored the experimental scene in relation to their subjective feelings. This study assesses the rationality of the questionnaire based on three main perceptual dimensions (comfort, content, and familiarity) proposed by Torresin [75]. The first refers to the pleasantness or comfort of the surroundings, the second refers to the environment and sounds or events, and the third refers to the familiarity and duration of exposure to the environment or events. The content of this assessment scale already contains these and is applicable to use for indoor soundscape assessment. Since single visual and single auditory are only used as stimulus elements, the scale is not used.

2.2.5. Experimental procedure

The experimental environment in this study was arranged in an indoor space to avoid interference from other factors. The subjects conducted the experiment in a comfortable sitting position, maintained normal breathing, and wore sensors for body part stability to ensure good electrode contact. During the experiment, we collected physiological data from subjects for 2 minutes before stimulation as normalized baseline data. Then, the formal experiment was entered, and the experimental process was divided into an experiential phase and an evaluation phase. In the experiential phase, each subject was required to independently experience and complete the scale assessment. Subjects wore the experimental equipment and experienced each experimental material in a relaxed state for a duration of 1 minute each. The total duration of the experiment was 50 minutes (Including time for rest and adjustment). In the process of the stimulation, the physiological data of the subjects were recorded at the same time. The evaluation phase is that after the experience, the subjects were required to fill in the Perceived Restorative Soundscape Scale and the Subjective Preference Scale. Specific details are shown in Fig 1.

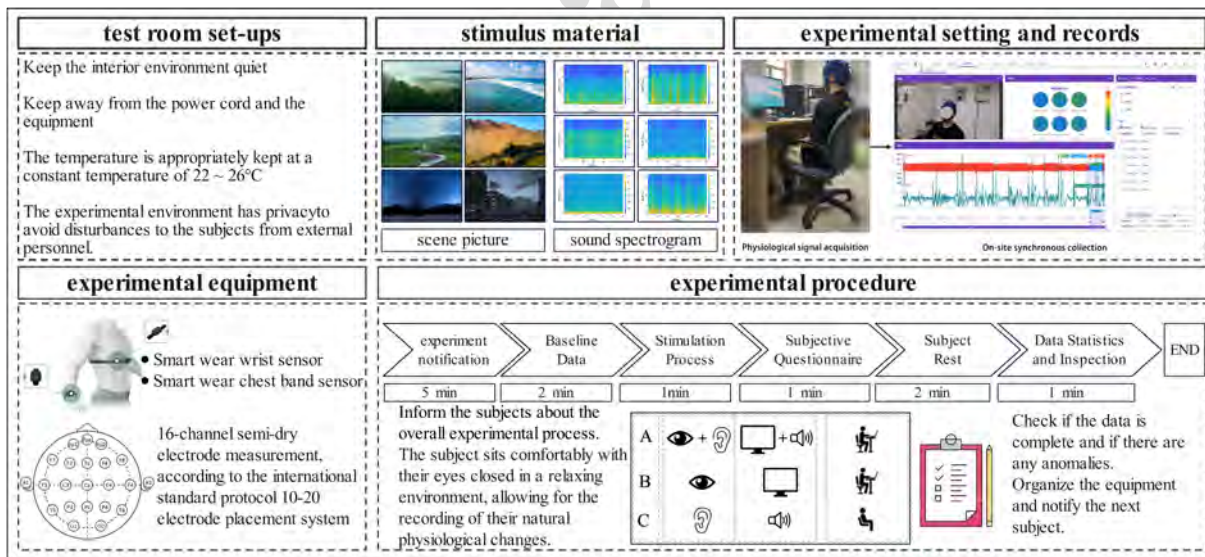


Figure 1: Stimulus material, test room set-ups, and experimental procedure

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2.3. Data processing and analysis

Since the baseline physiological data varied greatly between subjects, to ensure the accuracy of the study, the physiological data were first normalized to remove individual differences. Change data before and after stimulation Δ was calculated according to the formula (1):

$$\Delta\% = (PSV - BSV) / BSV * 100 \quad (1)$$

Where Δ indicates the rate of change of indicators before and after stimulation; PSV indicates 1 minute of physiological signal data during stimulation; BSV indicates baseline data recorded 2 minutes before stimulation.

In this study, the assumptions of normality (Shapiro-Wilk and Kolmogorov-Smirnov tests) and homoscedasticity (Levene) were first tested by SPSS 24.0 software. The normality assumption was satisfied and parametric tests were performed accordingly. T-tests were performed on paired samples of physiological metrics to compare the data from the baseline period with the data during stimulation. After screening out the indicators with significant differences, the changes between each experimental stimulus and these indicators were obtained through statistical analysis. Finally, a one-way ANOVA and LSD post hoc test were performed to determine the pairwise significance under different indicators.

The preference scale was first tested for reliability and validity, and a main effects test was conducted for stimulus modality and scene type, followed by a mean analysis of the participants' scores to explore their effects on the subjects' subjective preference. When analyzing the subjective restorative scale, the scale was first tested for reliability and validity, and then the subjective factors were obtained through the perceived restorative scale questions. The weight distribution and intrinsic connection between physiological indicators and subjective evaluations were verified by performing a typical correlation analysis between the two.

3. Results

3.1. Significance test for physiological indicators

Table 1: Paired Sample T-test of Physiological Indicators

Indicator Type	Stimulus Modality	Baseline M(SD)	Forest M(SD)	Ocean M(SD)	Grassland M(SD)	Desert M(SD)	Starry sky M(SD)	Urban M(SD)
SCL	Audiovisual	6.09 (4.96)	5.33 (4.34)*	5.92 (4.55)	5.12 (4.26)	6.02 (4.82)	6.17 (4.93)	6.26 (4.64)
	Visual	5.79 (4.66)	5.39 (4.73)*	4.67 (4.44)*	4.60 (3.63)*	4.46 (3.29)*	4.93 (4.86)	4.43 (3.79)*
	Auditory	5.64 (4.62)	5.48 (5.11)	4.73 (4.02)*	4.27 (3.92)*	4.51 (4.56)*	4.63 (4.29)*	4.67 (4.17)*
SCR	Audiovisual	0.40 (0.36)	0.32 (0.42)	0.30 (0.31)	0.28 (0.35)	0.41 (0.69)	0.32 (0.29)*	0.44 (0.64)
	Visual	0.45 (0.53)	0.43 (0.57)	0.22 (0.27)*	0.28 (0.39)	0.24 (0.25)*	0.33 (0.66)	0.24 (0.29)*
	Auditory	0.35 (0.40)	0.39 (0.58)	0.28 (0.39)	0.33 (0.54)	0.28 (0.34)	0.35 (0.64)	0.42 (0.75)
RF	Audiovisual	10.95 (1.34)	10.96 (1.79)	10.49 (2.16)	9.83 (3.44)	9.18 (3.60)*	9.24 (4.24)	10.20 (3.13)
	Visual	10.35 (1.60)	10.67 (2.33)	11.24 (3.33)	10.39 (2.52)	10.52 (3.34)	9.44 (3.94)	10.09 (2.13)
	Auditory	10.16 (2.53)	10.76 (3.88)	10.87 (3.24)	9.71 (2.61)	10.40 (2.17)	10.49 (2.59)	11.79 (3.14)
RD	Audiovisual	10.63 (2.72)	11.47 (1.53)	10.77 (3.06)	9.48 (3.08)	10.01 (4.69)	9.92 (4.67)	9.37 (3.13)

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Table 1: Paired Sample T-test of Physiological Indicators

Indicator Type	Stimulus Modality	Baseline M(SD)	Forest M(SD)	Ocean M(SD)	Grassland M(SD)	Desert M(SD)	Starry sky M(SD)	Urban M(SD)
	Visual	11.37 (3.31)	9.42 (3.75)	9.07 (3.52)*	7.60 (4.34)*	6.50 (3.96)*	7.33 (4.04)*	8.88 (3.02)*
	Auditory	10.15 (3.86)	7.09 (4.03)*	8.13 (3.52)	7.70 (3.57)*	7.81 (3.13)	9.92 (2.94)	7.25 (3.80)*
	Audiovisual	34.84 (1.09)	34.86 (1.10)*	34.93 (1.07)*	34.97 (1.08)*	35.02 (1.05)*	35.06 (1.05)*	35.08 (1.05)*
SKT	Visual	34.48 (1.30)	34.51 (1.29)*	34.54 (1.28)*	34.56 (1.27)*	34.59 (1.26)*	34.61 (1.24)*	34.64 (1.23)*
	Auditory	34.64 (1.25)	34.75 (1.18)	34.29 (2.86)	34.65 (1.31)	34.64 (1.09)	34.82 (1.16)	34.47 (2.00)
	Audiovisual	81.20 (12.94)	81.05 (12.25)	80.85 (11.64)	80.70 (11.71)	81.85 (11.67)	79.35 (11.9)*	80.15 (12.09)
HR	Visual	81.05 (11.12)	79.80 (11.57)	80.40 (12.08)	80.75 (12.00)	81.45 (11.55)	81.25 (12.49)	80.75 (12.16)
	Auditory	80.15 (11.39)	80.35 (11.57)	79.30 (12.03)	81.05 (13.48)	81.45 (12.48)	81.05 (12.48)	81.70 (11.24)
	Audiovisual	51.76 (24.14)	45.57 (21.66)	46.34 (19.39)	45.20 (17.22)*	43.89 (20.06)*	47.04 (19.94)	43.19 (24.03)*
SDNN	Visual	47.04 (18.71)	42.29 (22.01)	45.89 (27.01)	39.86 (21.90)*	41.60 (23.79)	39.71 (20.50)	36.77 (13.82)*
	Auditory	51.55 (28.08)	40.75 (17.81)	51.66 (42.94)	39.40 (18.90)*	35.29 (16.75)*	41.86 (19.23)	40.28 (19.19)
	Audiovisual	43.49 (25.33)	39.46 (21.33)	39.50 (20.14)	37.27 (17.38)	35.19 (16.47)*	41.11 (21.23)	40.74 (27.94)
RMSSD	Visual	34.50 (16.58)	36.43 (18.65)	36.15 (18.80)	35.70 (23.08)	34.86 (21.32)	32.47 (16.74)	31.87 (16.36)
	Auditory	37.35 (18.48)	36.87 (17.70)	47.65 (38.44)	35.29 (17.91)	32.59 (17.35)*	37.04 (20.11)	34.27 (17.93)
	Audiovisual	21.13 (19.22)	21.74 (21.23)	20.32 (17.30)	18.98 (17.90)	17.12 (16.01)	22.60 (19.49)	20.15 (18.92)
PNN50	Visual	15.00 (15.98)	18.78 (19.73)	20.33 (19.93)*	17.32 (21.02)	16.99 (18.89)	14.95 (18.50)	15.71 (19.37)
	Auditory	19.31 (18.74)	18.87 (18.11)	25.80 (24.86)*	19.00 (17.79)	17.97 (20.95)	21.34 (23.00)	16.36 (16.12)
	Audiovisual	755.05 (115.39)	756.10 (109.50)	755.60 (102.19)	757.73 (101.51)	747.16 (101.32)	771.41 (112.49)*	764.88 (111.88)
IBI	Visual	752.19 (96.23)	765.99 (102.88)	761.06 (106.62)	758.74 (110.60)	750.59 (103.54)	754.47 (114.80)	758.36 (110.11)
	Auditory	761.31 (103.99)	761.03 (103.70)	771.78 (107.27)	757.64 (117.47)	752.25 (113.31)	755.56 (110.89)	745.76 (94.55)
	Audiovisual	974.19 (579.66)	593.52 (726.98)*	884.93 (970.38)	1054.69 (1332.87)	985.15 (2042.18)	1101.40 (1328.71)	699.35 (763.07)
LF	Visual	874.36 (981.24)	1082.12 (1649.12)	936.37 (1171.83)	680.75 (836.27)	1434.80 (3131.54)	1042.83 (2298.50)	535.27 (659.40)

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Table 1: Paired Sample T-test of Physiological Indicators

Indicator Type	Stimulus Modality	Baseline M(SD)	Forest M(SD)	Ocean M(SD)	Grassland M(SD)	Desert M(SD)	Starry sky M(SD)	Urban M(SD)
	Auditory	901.43 (1095.16)	765.85 (812.54)	4834.00 (16502.57)	1012.06 (1403.48)	500.80 (864.08)	594.54 (733.41)	885.80 (1223.30)
HF	Audiovisual	553.48 (377.45)	717.83 (668.79)	691.42 (703.76)	565.17 (418.58)	584.15 (503.86)	598.63 (391.81)	586.62 (504.84)
	Visual	584.11 (440.40)	860.67 (881.05)	665.69 (626.64)	577.15 (578.69)	627.03 (712.64)	526.67 (545.10)	512.66 (428.64)
	Auditory	682.95 (536.42)	561.66 (444.24)	1302.70 (2352.30)	583.01 (442.28)	471.30 (361.66)*	643.39 (561.44)	473.73 (339.93)*
LF/HF	Audiovisual	3.07 (3.55)	1.05 (1.07)*	2.79 (3.45)	2.84 (3.44)	1.76 (1.75)*	2.76 (3.53)	1.94 (1.90)
	Visual	2.64 (3.36)	2.62 (4.18)	3.06 (5.25)	1.88 (2.24)	2.75 (4.15)	2.52 (3.22)	1.76 (2.32)
	Auditory	2.31 (2.97)	2.56 (3.75)	1.61 (1.82)	3.85 (9.43)	1.29 (1.21)	1.88 (2.59)	2.75 (4.08)

Note: * denotes $P < 0.05$, indicating significance between data.

As shown in Table 1, the paired samples t-test revealed significant differences in the SCL indicator. Specifically, Significant differences were found in the audiovisual stimulation of the forest scene, the visual stimulation of forest, ocean, grassland, and desert, and the auditory stimulation of ocean, grassland, desert, and starry sky. From the SCR indicator, audiovisual stimulation of the starry sky, and visual stimulation of the ocean and desert are significantly different. From the RF indicator, only the desert scene with audiovisual stimuli was significantly different before and after stimulation. From the RD indicator, the visual stimulation of ocean, grassland, desert, and starry sky have significant differences, and the auditory stimulation of forest have significant differences. From the SKT indicator, the audiovisual stimulation and visual stimulation of forest, ocean, grassland, desert, and starry sky have significant differences. From the HR indicator, there was a significant difference after the audiovisual stimulation of the starry sky scene ($p < 0.05$), with a decrease in heart rate after the stimulation compared to before the stimulation ($M = 81.2$), suggesting that the subjects were more likely to enter a relaxed state. With audiovisual stimulation, the heart rate decreased after stimulation in all scenes except the desert scene. After auditory stimulation, only the ocean scene showed a lower HR than the baseline period, and the overall change was not significant.

From the SDNN indicator, there was a significant difference in the three stimulus modalities for the grassland scenes, while the desert was significantly different in the audiovisual and auditory stimulation, and the urban was significantly different after the audiovisual and visual stimulation. From the RMSSD indicator, the desert differed significantly in the audiovisual and auditory stimulation. From the PNN50 indicator, the grassland scene has significant differences in visual and auditory stimulation. From the LF indicator, the ocean scene was significant in the visual and auditory stimulation. From the IBI indicator, there is a significant difference between before and after the starry sky audiovisual stimulation ($p < 0.05$). From the HF indicator, desert and urban were significant in auditory stimulation differences. From the LF/HF indicator, the forest and the desert were significant after the audiovisual stimulation. Taken together, forest, ocean, and starry sky can be categorized as scenes with good physiological recovery, while grassland, desert, and urban can be categorized as scenes with average physiological recovery.

3.2. ECG and RESP indicators analysis

Through statistical analysis, it was found that the changes in HR and IBI indicators were not obvious. The study found that these two indicators are easily affected by more factors, so they were not included in the judgment criteria. The data in Fig 2 show that the PNN50 of the forest, ocean, and starry sky scenes under the three stimulus modalities increased by more than 10% (except for the forest scene with auditory stimulation), which indicates that the subjects were in a state of relaxation and pleasure in the scene, indicating that the body was in a restorative state. The desert with audiovisual stimulation and the city with auditory stimulation showed decreases of greater than 10% in both indicators, and the participants felt some tension under these two stimuli. The RMSSD values of the three scenes, forest, ocean,

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and starry sky, were elevated in response to audiovisual stimuli and auditory stimuli. The forest and desert scenes under visual stimulation had their RMSSD elevated. However, the magnitude of change was small, indicating that this indicator was used for evaluating effectiveness lower than the PNN50 indicator. The two indicators increased by more than 10% after auditory stimulation in the ocean scene, and ocean sound is the auditory scene with the best effect in promoting recovery.

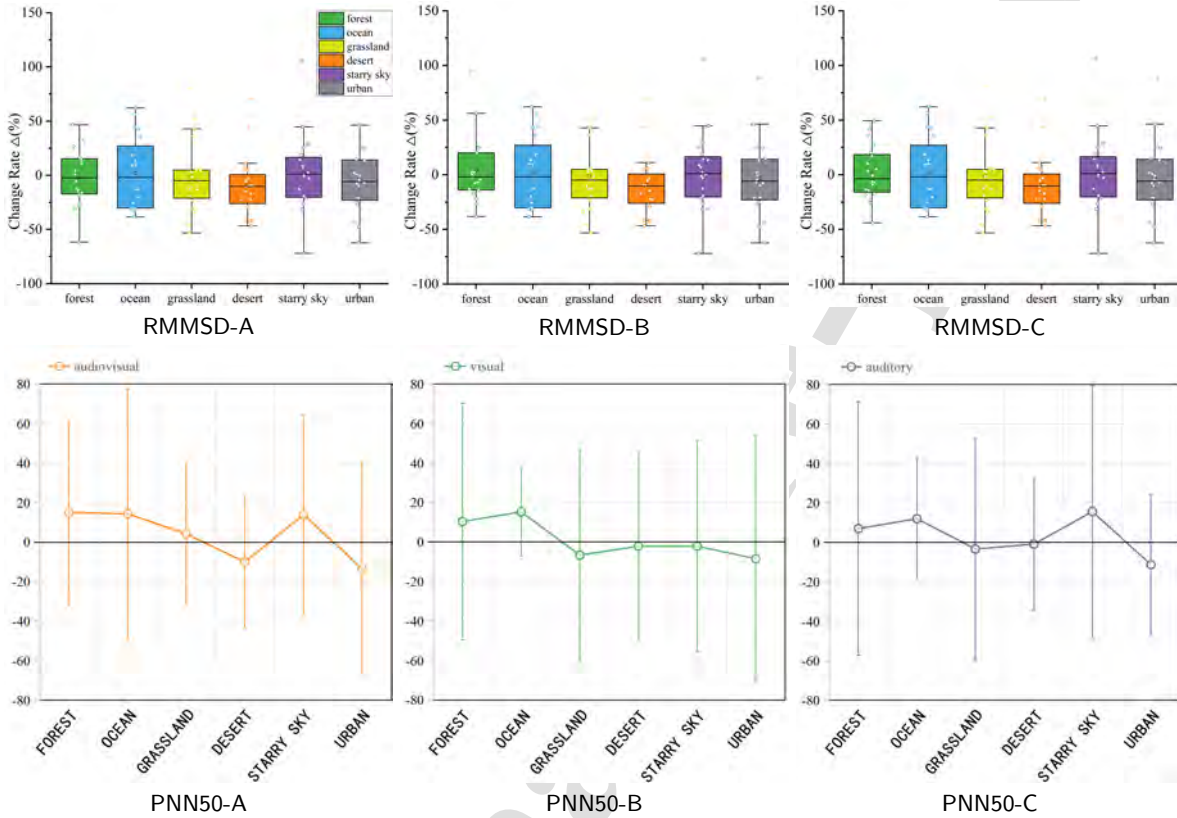


Figure 2: Results of RMSSD, PNN50 for different scene types under three stimulus modalities. (1)RMSSD is the root-mean-square of the difference between adjacent normal cardiac cycles. (2)PNN50 indicates the proportion of heartbeats that differ by more than 50 milliseconds between two adjacent intervals (NN intervals).

As shown in Fig 3, with audiovisual and visual stimulation, HF power increased and LF/HF ratio decreased in most of the scene, indicating that subjects were in a relaxed state. However, the enhancement effect of audiovisual stimulation was better than that of single visual stimulation. After auditory stimulation in the urban scene, the subjects' HF power decreased by 20% and the LF/HF ratio increased by 20%, indicating that the subjects were in a tense, alert state. However, it should be noted that there is no consistency in the changes of the two indicators after stimulation of both grassland and desert scenes.

After normalizing the subjects' RF and RD, the results were obtained as shown in Fig 4. Compared with single visual and single auditory stimulation, after audiovisual stimulation, the subjects' RF changed less than before stimulation, and both were less than 5%, which indicated that the subjects felt relaxed or quiet, and the RF became more stable and regular. Under audiovisual and visual stimulation, the urban scene of RF was almost unchanged, while after auditory stimulation, the urban scene of RF increased substantially and the subjects breathed faster. By analyzing the RD results, it was found that six scenes in the audiovisual stimulation increased, with forest, ocean, and starry sky increasing by more than 15% compared to the other three scenes. RD decreased by more than 20% in the other two single-stimulus modalities, except for the starry sky scene with auditory stimulation. In addition, the RD changes of the six scenes in each stimulus modality showed consistency.

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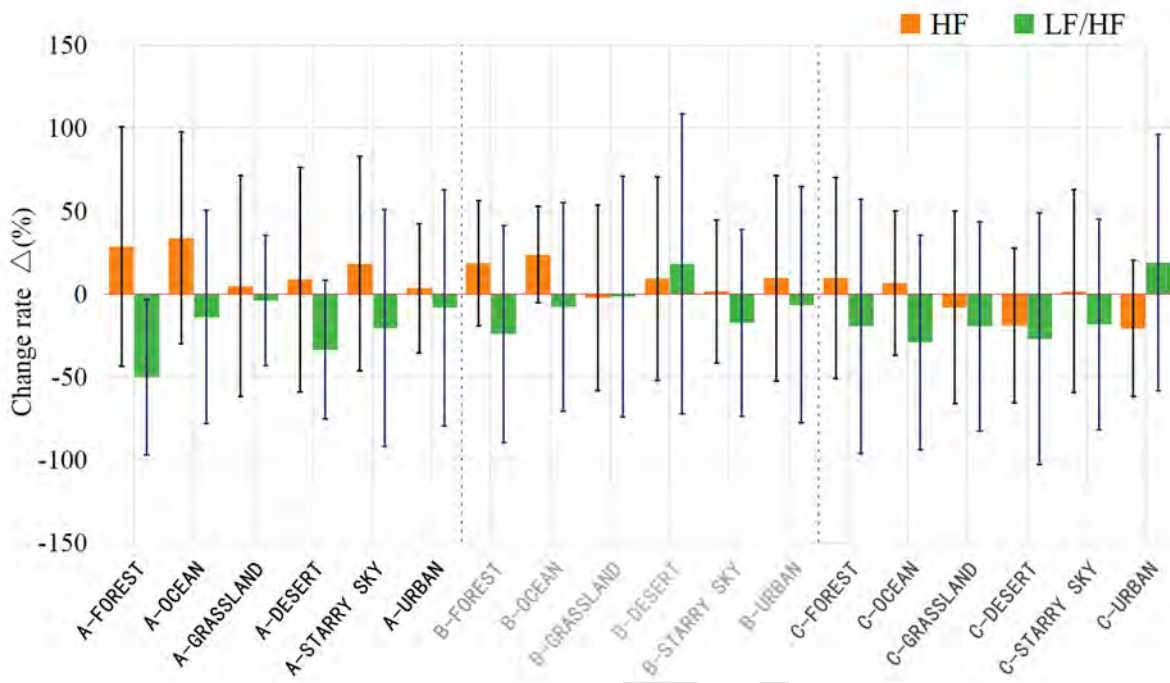


Figure 3: HF, LF/HF results for different scene types with three stimulus modalities. HF: high-frequency power. LF/HF: the ratio of low-frequency to high-frequency power, indicating the relative activity levels of the sympathetic and parasympathetic nervous systems.

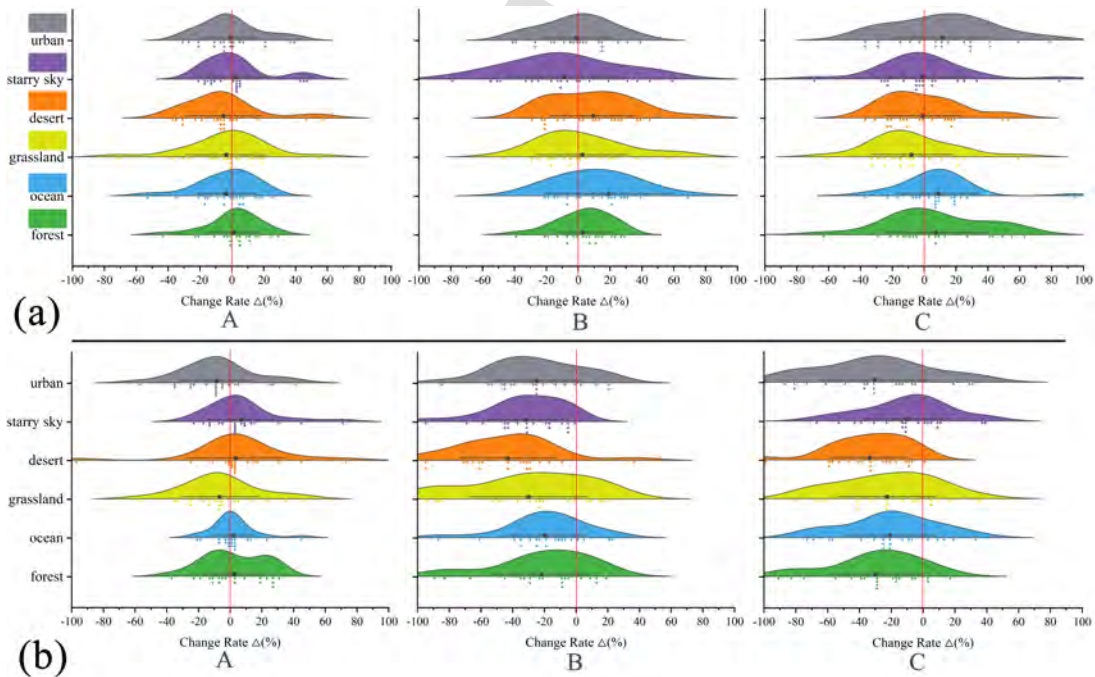


Figure 4: RESP results for different scene types with three stimulus modalities. (a) Respiratory frequency: calculated from the peak-to-peak distance of the respiratory wave. (b) Respiratory depth: calculated from the amplitude of the respiratory wave.

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3.3. EEG and eye movement indicators analysis

After the subjects' data were processed, the changes in TBR for all electrodes were examined, and the results showed that the differences between TBR under different types of stimuli were not significant ($p > 0.05$), and there were no significant differences in post hoc multiple comparisons. A possible reason for this is that the changes in brain waves are relatively stable, and the overall changes in the quiet state are small, and there is no significant difference in the subjects' attention as affected by the type of scene.

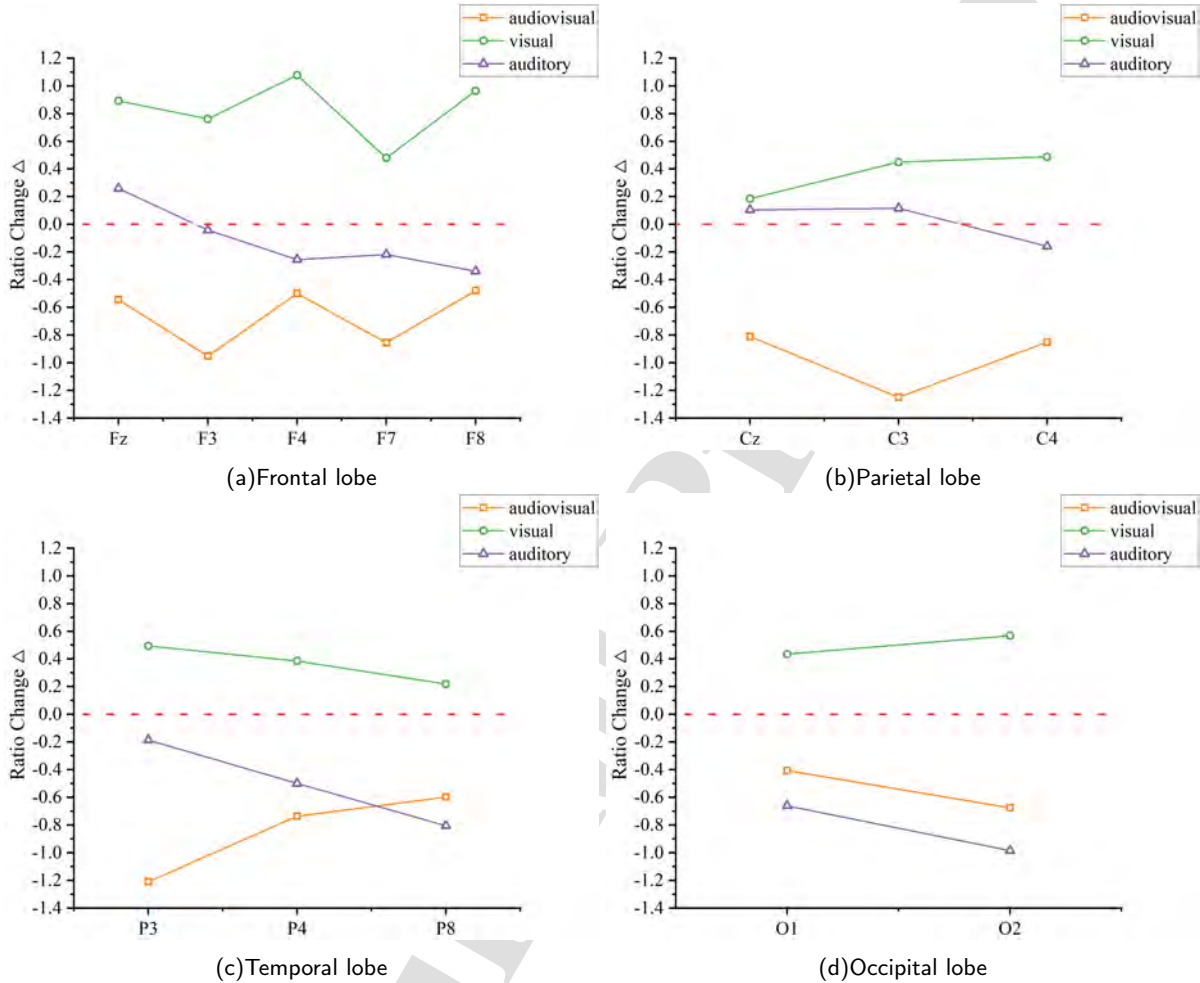


Figure 5: Results of pre-TBR and post-TBR stimulation changes in each channel under different brain regions. TBR: θ/β , the lower the value, the more focused the attention.

As shown in Fig 5, the between-group analysis of the three stimulus modalities showed that except for Pz, Fpz, and P7, the other channels were significantly different ($p < 0.05$). The TBR of all four brain regions decreased under audiovisual stimulation, and the degree of decrease was greater in the frontal and parietal regions than in the auditory stimulation. And there was an increase in TBR in all of them under visual stimulation. The (Fz, F3, F4, F7, F8) of the frontal lobe region had the highest degree of increase in TBR and the most severe increase in the level of attention in response to a visual stimulus, the (P3, P4, P7) of the temporal lobe region, which is a brain area for auditory processing, had the least change in response to a single visual stimulus, and the decrease in TBR was approximately the same in the other two types of stimulation. The (O1, O2) of the occipital lobe region mainly reflected the visual information in the brain, and the magnitude of TBR decrease after auditory stimulation was larger than the other two stimuli. There is consistency in the attentional changes of different brain regions under the same sensory stimuli.

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The changes in fatigue factor R-values are shown in Fig 6. With audiovisual stimulation, the R-values of all six scenes were reduced, and the subjects' fatigue was relieved after the stimulation. Among them, the forest and ocean scenes R-values decreased by 1.09 and 1.37 respectively, much higher than the other four scenes. The starry sky scene R-value decreased by 0.53, which was the smallest decrease. Under the visual stimulation, R-values of the forest and ocean scenes increased by 0.53 and 0.24, respectively, and subjects' fatigue increased after the stimulus. The R-values of the six scenes under the auditory stimulation did not change significantly.

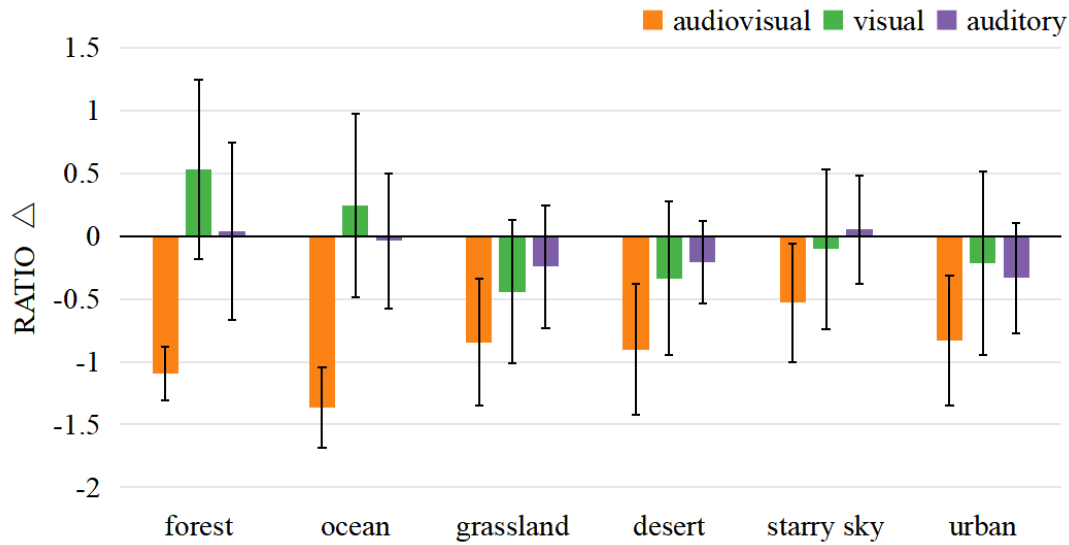


Figure 6: Changes in R-value before and after stimulation. R-value: $(\alpha + \theta)/\beta$, the higher the value, the greater the degree of human fatigue.

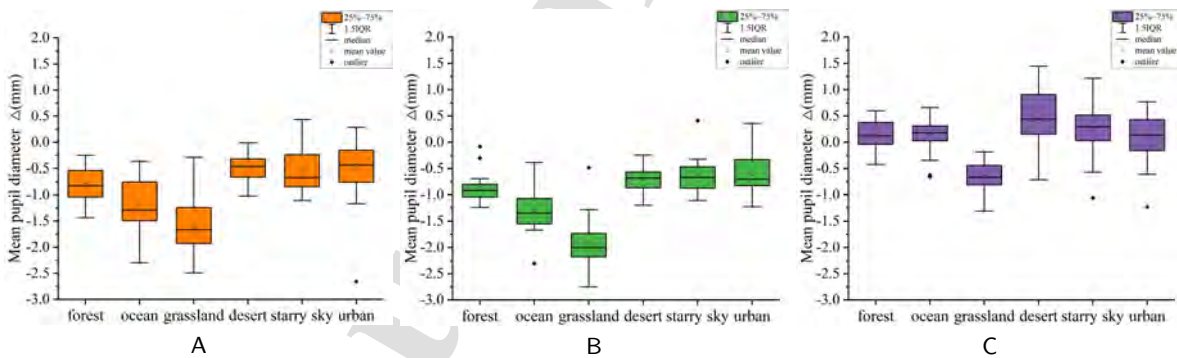


Figure 7: Change in mean pupil diameter before and after stimulation

The statistics of the mean pupil diameter in the three stimulus modalities are shown in Fig 7. Significance between different scenes was found by ANOVA analysis ($p < 0.05$), and between-group differences were much greater than within-group differences ($F = 45.01$). The average pupil diameter of the audiovisual stimulation groups all decreased compared with the pre-stimulation, and the average values of the forest, ocean, grassland, and starry sky scenes were -0.796, -1.180, -1.610, and -0.537, respectively. The box plots of the ocean scene were the largest, with a discrete and fluctuating distribution of data, and the opposite was true for the desert scene. The average pupil diameter of the visual stimulus decreased to a greater extent than that of the audiovisual stimulus, with mean values of -0.828, -1.228, and -1.876 for the forest, ocean, and grassland, respectively. In addition, the box plots were smaller than those for the audiovisual stimulus and the data were more concentrated. There were more outliers in this group, and this modality

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tends to increase the pupil of individual subjects. The mean pupil diameter of the auditory stimulation group (except for the grassland scene) increased by 0.085 ~ 0.451 mm on average for the five types after stimulation, with the desert group showing the greatest increase in mean pupil diameter. The urban scene had the lowest magnitude of effect on the subjects after stimulation, with mean values of -0.505, -0.594, and 0.085 for the three groups, respectively. Comparing the three stimulus modalities, there was a consistency in the trend of mean pupil diameter across scenes.

3.4. Preference questionnaire analysis

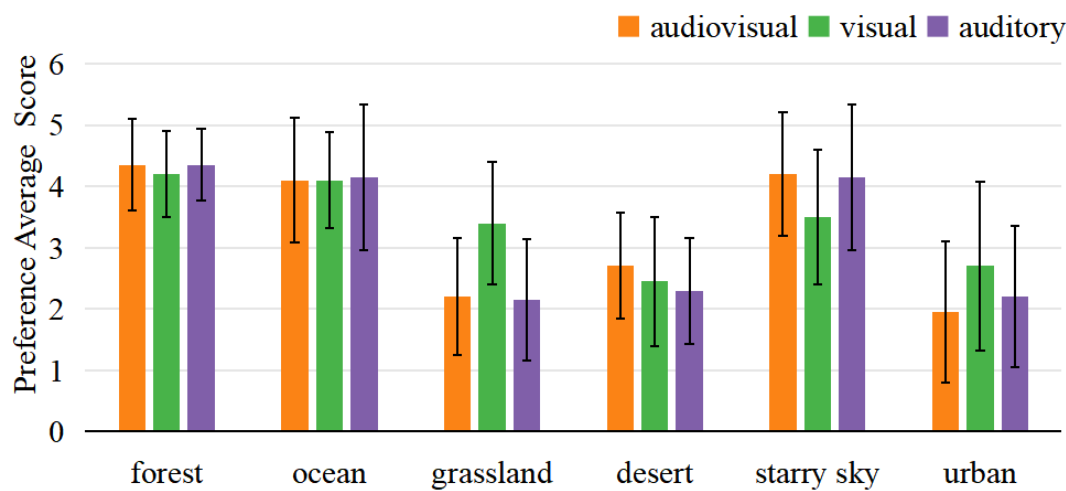


Figure 8: Preference scores for the six scene types under the three stimulus modalities

ANOVA analysis of the scores for each stimulus modality showed significant results ($P < 0.05$). As shown in Fig 8 are the preference scores for the six types of scenes under the three stimulus modalities, the mean of the total preference scale scores for the three stimulus modalities for the forest scene were 4.35, 4.2, and 4.35, respectively, which were higher than those for the other five scenes, and the standard deviations were 0.745, 0.696, and 0.587, respectively, with a small degree of dispersion in the data, which indicated that the participants had a high degree of favoritism for the scene. The preference scores for the ocean scene and the starry sky scene are slightly lower than those of the forest, with a score of about 4.00, indicating that they are also easy to accept by the participants. However, the standard deviation is increased by 13.2% ~ 98% compared to the forest scene, with an increase in the degree of dispersion, which indicates that the scoring of the participants for these scenes is more dispersed, with an increase in the bias in the degree of subjective favoritism. In addition, the scores of grassland, desert, and urban scenes were lower. The standard deviations of the three stimulus modalities for the urban scene were 1.146, 1.197, and 1.415, respectively, indicating that the distribution of the scores scored by individuals around the mean was more dispersed, with greater differences between individuals, and that the variability of the intensity of individuals' perceptions of the urban scene was higher.

As can be seen from the between-subjects effect test for preference shown in Table 2, the effect of the three stimulus modalities ($p = 0.357 > 0.05$) on subject preference scoring was not significant, indicating that the stimulus modalities had essentially no effect on the user's subjective preference, and there was no significant interaction effect. The effect of soundscape type on subject preference scoring showed significance ($p = 0.000 < 0.05$) and showed much greater differences between groups than within groups ($F = 51.411$). The combined term of soundscape type and stimulus modality showed significance ($F = 3.173$, $p = 0.001 < 0.05$), suggesting that there was an interaction effect between these two sources of variance and subject preference, indicating that the effect of stimulus modality on preference depended on the level of scene type.

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Table 2

Analysis of between-subjects effects of stimulus modality and scene type (Dependent variable: perceived preference)

Differential source	Type III sum of squares	df	mean square	F	p
Correction Model	292.081a	17	17.181	17.109	0.000**
modality	2.072	2	1.036	1.032	0.357
type	258.147	5	51.629	51.411	0.000**
modality & type	31.861	10	3.186	3.173	0.001**

The Correction Model contains all main effects and interaction effects.
a: $R^2 = 0.460$ (adjusted $R^2 = 0.433$) indicates moderately high explanatory power.
** denotes $p < 0.005$, indicating significance between data.

Table 3

Reliability and validity parameters of the PRSS

Factor	Cronbach's alpha coefficient	KMO criterion	Bartlett's test of sphericity	Number of items
Fascination	0.933	0.875	0.000	5
Being-Away-To	Corrected 0.466	Corrected 0.500	0.000	2
Being-Away-From	0.939	0.771	0.000	4
Compatibility	0.808	0.687	0.000	4
Coherency	0.890	0.733	0.000	3
Scope	/	/	/	1
Total	0.927	0.932	0.000	18

3.5. Correlation relationship between physiological indicators and subjective evaluation with audiovisual stimuli

In this study, we considered the audiovisual stimulus as a complete soundscape. After checking the completeness of the PRSS, the valid scales obtained were analyzed for reliability and validity. The reliability of the scale was based on the Cronbach alpha coefficient and the structural validity was based on the KMO test, and the results obtained are shown in Table 3. The overall reliability of the scale was high (Cronbach alpha coefficient = 0.927), and the structural validity of the scale was also high, with a corresponding KMO criterion of 0.932. The sixth dimension could not be used to determine the reliability and validity parameters of the questionnaire because there was only one item in the range factor. However, except for the Being-Away-To, the reliability and validity of all the other dimensions obtained corresponding values (> 0.7). Through subsequent analysis and interviews with the participants, we found that there was a certain deviation between the formulation of this item and the participant's understanding of the item, resulting in the item's reliability and validity not meeting the standards, and therefore a subsequent correction was made.

In order to establish a link between physiological indicators and subjective evaluations, a typical correlation analysis between physiological indicators and subjective evaluations was performed. Physiological indicators included SCL, SCR, HR, SDNN, RMSSD, PNN50, HF, LF/HF, RF, and RD. These physiological metrics were determined based on the significance obtained from paired-sample t-tests of previous physiological metrics. SKT was found to be unaffected by soundscape type in the available studies and therefore was not included [76]. The subjective evaluation consists of Fascination, Being-Away-To, Being-Away-From, Compatibility, Consistency, and Scope. Typical correlation analyses were performed, and the typical loadings are shown in Fig 9. To clearly understand the results of the typical correlation analysis, the findings were interpreted by focusing on variables with typical loadings of 0.4 or higher. The correlation coefficient between the physiological and subjective factors of the typical structure was 0.492. The physiological indicators that produced the strongest effects were SCR, RMSSD, PNN50, and RD. The subjective group consisted mainly of Being-Away-From, Compatibility, and Coherency, which suggests that the higher the subjective evaluative factors (e.g., Being-Away-From) score is higher, the higher the probability that SCR and RMSSD decrease while RD increases.

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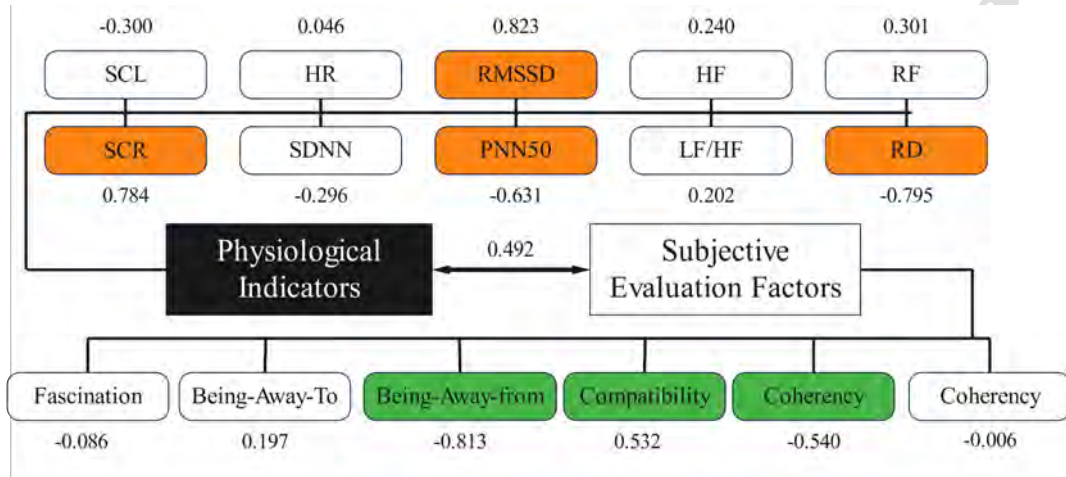


Figure 9: Structural plots depicting the results of the canonical correlation analysis

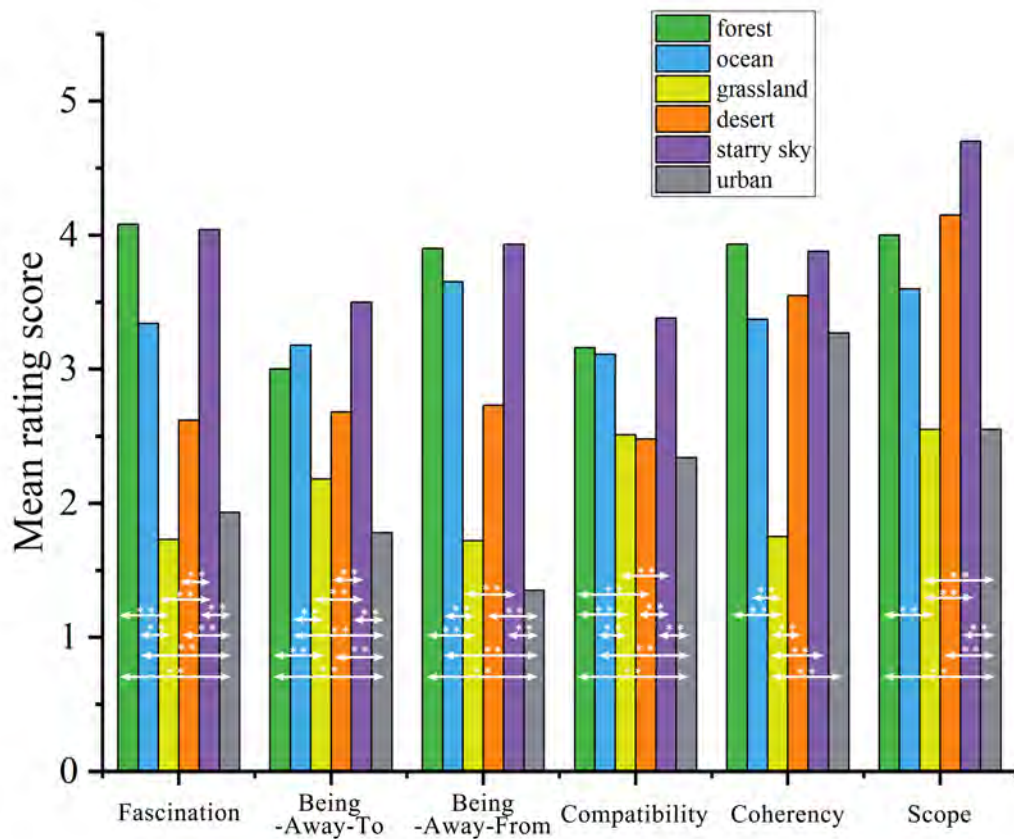


Figure 10: Perceived restorative soundscape scale (PRSS) item.**denotes $p < 0.01$, indicating significance between data.

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Fig 10 visually illustrates the mean Perceptual Restorative Soundscape Scale (PRSS) scores for the six domains, which were analyzed and found to be generally significantly different. “Fascination” refers to the ability of the environment to hold one’s attention, which can be interpreted as the experimental material having the sensation of being intriguing and subjects being able to focus easily without exhausting their brain resources. The “Fascination” of forest, ocean, and starry sky are 4.08, 3.34, and 4.04 respectively, which are more attractive than the other types, and these three types of environments are more compatible with the participants’ expectations and goals. Similarly, there is also consistency in the Be-Away-to and Be-Away-From domains, but the starry sky has the highest mean scores in Be-Away-to and Be-Away-From, with 3.50 and 3.93 respectively. “Be-Away-From” means that the environment can withdraw from the current environment to other environments, which can be interpreted as the experimental materials are not the same as those encountered in daily life, and the experimental materials are not the same as those encountered in daily life, so that the subjects have the feeling of being temporarily removed from the tedious life, and “Be-Away-From” has the largest difference among all the domains.

“Compatibility” means that there is a commonality between the environment and the individual’s feelings. When compatibility is increased, the differences in the surrounding environment are weakened so that the individual does not have to concentrate too much, and psychological recovery is ultimately achieved. The score difference in this domain is the smallest among all domains, and the three types of forest, ocean, and starry sky have a “Compatibility” of 3.16, 3.11, and 3.38, respectively, which is more in line with the subjects’ relaxation preferences. The other three types of scenes had similar scores and produced the same level of environmental identity for the subjects. “Coherency” refers to the relevance of the elements of the environment to its structure and organization. Only the Grassland scene scored extremely low in this domain, while the other scenes all scored greater than 3, suggesting that the choice of experimental materials for this type of experiment is somewhat limited. “Scope” refers to an environment that has a certain scale, which enables subjects to feel that it can extend to a certain extent in the spatial or temporal dimensions. The scores of the starry sky and city types in this domain are 4.70 and 2.55 respectively, and this suggests that in the starry sky type of stimuli, the subjects have a low level of spatial confinement and can get more comfortable relaxation. The three scenes with high scores were forest, ocean, and starry sky at 3.68, 3.37, and 3.91, respectively, suggesting better psychological restorative effects, while the urban scene had a mean PRSS score of 2.55 and a poor subjective perception rating.

3.6. Correlation analysis of physiological indicators

Spearman’s correlation analysis was performed on the physiological indicators and the results are shown in Fig 11. Since the three stimulus modalities involved different senses, they were analyzed separately. There were significant correlations between the ECG-related indicators (RMSSD, PNN50, and HF) in the three stimulus modalities. Whereas, the highest correlations between the different metrics were found under audiovisual stimulation. Under audiovisual stimulation, RD was positively correlated with RMSSD, PNN50, and HF, and R-value was negatively correlated with LF/HF. Under visual stimulation, RD was positively correlated with R values. In addition, pupil diameter was positively correlated with RF with a correlation coefficient of 0.99, a very strong correlation. These indicators were both somewhat correlated and showed independent response characteristics. Under the same stimulus modality, there were differences in response speed, response strength, and response priority of different indicators.

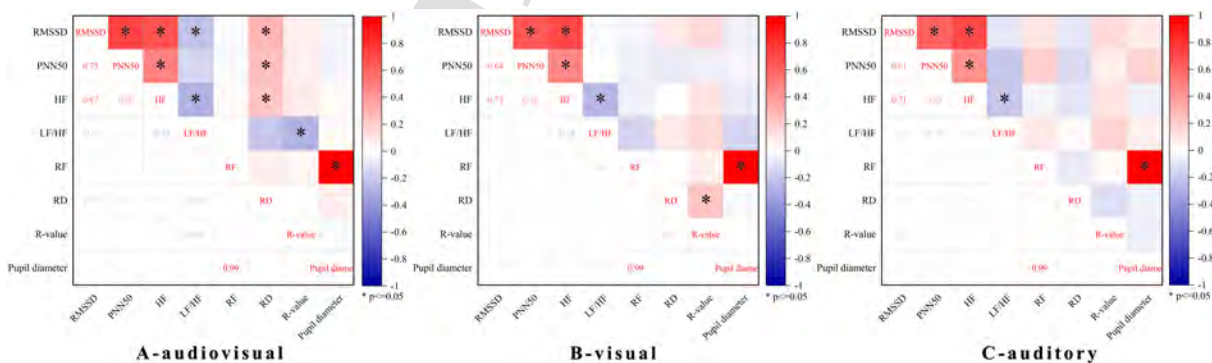


Figure 11: Heatmap of correlation between metrics in three stimulus modalities

4. Discussion

When human physiology enters the recovery state, the whole body is in a state of fatigue, less alert to the outside world, immersed in a certain environment, but maintains a certain level of attention, with a certain degree of arousal, able to rejuvenate and relieve fatigue in a relatively short period of time. There is a difference with the night sleep, after waking up can quickly return to the previous state.

4.1. Effect of stimulus modalities on physiological recovery

By comparing the three stimulus modalities, the results of the five metrics, RMSSD, HF, LF/HF, RF, and R-value, indicated that audiovisual stimulation produced a more stable recovery benefit for participants compared to the other two modalities, with an increase in RMSSD and HF, a decrease in LF/HF and R-value, and little to no change in RF, after stimulation. This is consistent with findings from previous studies ([77],[78],[79]). Participants' subjective satisfaction was higher with audiovisual stimuli, indicating some degree of detachment from the current daily urban environment. Appropriate audiovisual stimuli need to be controlled for the right duration and should not elicit a strong sense of presence, as arousal is lower compared to anxiety-inducing stimuli [80]. The stimulus material needs to maintain a certain level of attention and interest in the participants, relieve their mental fatigue, and restore their depleted attention.

Visual and auditory senses work together in daily use. One reason that audiovisual conditions may lead to greater recovery benefits is that artificial stimuli weaken the real-world environment so that participants are subjectively less aware of the real-world environment around them, and audiovisual attention is focused on the given stimuli. When a single sense is used to perceive the environment, the unused senses increase sensitivity and produce a greater response to external stimuli [81]. Subjects reported in the experiment that single visual stimuli caused some stress to them, gradually developing some impatience, and that auditory stimuli were less influential than visual stimuli. In addition, the eye movement metrics showed consistent results, with a single visual stimulus more likely to cause fatigue than an audiovisual stimulus, and a single auditory stimulus more likely to enhance the participants' visual senses. The LF/HF also dropped by a certain magnitude after the auditory stimulus, second only to the audiovisual, suggesting that the elicited physiological recovery benefit was slightly lower than that of the audiovisual stimulus.

The audiovisual state requires spreading attention to both senses, but brain regions show reduced whole attentional changes. In the relaxed state, subjects can achieve a certain level of arousal, and the process of stimulation attention generated reduces fatigue [82]. The occipital region, which is responsible for processing visual information [83], is less visually disturbed during auditory stimulation and shows a greater decrease in TBR in the occipital region compared to audiovisual stimulation. And subject's pupil diameter increased. This region shows more attentional focus. With auditory input activating this region, there is a significant interaction between auditory and visual cortex during audiovisual stimulation [84]. This suggests that when performing activities that require vision, appropriate corresponding auditory stimuli can be added for better task performance. Frontal areas (Fz, F3, F4, F7, F8) reflect emotion and cognition, and the wide range of TBR variations in this area may be related to attentional and affective responses involving the integration of vision and hearing [85]. In addition, according to the sequential analysis of the three stimulation experiments, we observed that the subjects become fatigue and adapt to the stimulation after a period, and the participants will be prone to certain errors. In the correlation study of various physiological indicators, it was found that ECG as an indicator of recovery could show significant changes and the correlations among the indicators were close. The degree of correlation between ECG, RESP, and EEG was higher with multi-sensory stimulation than with uni-modal stimulation. It demonstrates better overall physiologic recovery and higher cardiac-related recovery sensitivity. Visual input produces stronger feedback and more associations with physiological changes than auditory for the same stimulus [86]. Stimuli affecting pupil diameter are closely related to respiratory rate, and there is a strong synchronization between these two indicators.

Therefore, spatial design should be based on audiovisual combination design, and combined with different spatial needs to rationalize the use of a single auditory. It is feasible to improve the fatigue or tension of the residents, to avoid the anxiety caused by a long period of time a single visual task to the human body should be a period of time of attention, arousal, interest as a starting point.

4.2. Effects of scene type on physiological indicators

In the study, forest, ocean, grassland, and desert were categorized as natural scenes, and starry sky and urban were categorized as man-made scenes, and significant differences between them could be observed. The forest, ocean, and starry sky scenes showed better physiological recovery of participants than the other three scenes in terms of

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PNN50, LF/HF, and average pupil diameter, resulting in a feeling of calmness and relaxation, as well as an increase in parasympathetic activity and inhibition of sympathetic activity [87][88]. In addition to traditional natural scenes, man-made scenes that match the subjects' favorites can also play a role in relieving fatigue and enhancing well-being [89]. The RMSSD and PNN50 of the desert scene, however, decreased substantially after audiovisual stimulation, which was significantly opposite to the results of other scenes, indicating that the participants' preference for the scene had a greater degree of influence on the human body metrics relative to the stimulus modality.

Any effective stimulus produces a sense of presence, including relaxation stimuli, as it leads to the activation of the motivational system that regulates attention. A lower TBR indicates that the participant's acceptance of the stimulus scene was increased, suggesting a greater sense of presence for that scene [90]. Stimulus modality dominates to a greater extent than scene type change. TBR is also positively correlated with wandering, with lower values representing increased attention to the task at hand [91]. And it has been hypothesized that it is not being completely in a relaxed state that is the best environment for recovery and that subjects in the presence of a relaxing stimulus with a low arousal level may be able to achieve better recovery.

Subjects have different cognitive experiences, they are more biased towards sensory perceptions that they are familiar with, and participants pay more attention to the types of scenes they prefer [92], with preference scales showing the same results. In addition, the greater the need for restoration, the more pronounced the environmental preferences of the participants will be [93]. Facing the same scene is also susceptible to subjective perceptions, with grassland scenes and desert scenes showing negative data changes in some indicators, contrary to the results of other indicators. Scene type has a significant effect on people's subjective preferences. They may subjectively dislike a certain scene type, but they may not have noticed that stimulus modality also has a positive effect on their objective metrics. In the analysis of the results of the eye movement metrics, it was found that participants were more influenced by the stimulus modality than the scene type, and the inconsistency may be due to the dominant experience of the visual elements, personal preference, and the degree of coordination of multi-sensory stimuli. People are more familiar with and have greater perceptual recovery from natural sounds and videos [94].

In addition, physiological indicators (SDNN, R-value, mean pupil diameter) found positive recovery responses in urban scenes, suggesting that urban have the potential to produce recovery effects [95][96]. As the subjects have all been living in the urban environment, life, stress, pollution, and other problems have made them bored and adapted [97][98]. The urban soundscape cognition is affected by the existing experience leading to the poor subjective evaluation obtained. Secondly, the experimental process reduces the loudness of urban sound in real environments, there exists the possibility of human physiological acceptance, and noise can be changed into a suitable sound in certain aspects. In addition, Kaplan [99] says that any environment can provide restorative conditions, and appropriate design and optimization of urban environments can be used for the health improvement of urban residents. Soothing sounds can be applied to increase the acceptance of viewers when they need to be presented with scenes that they do not like [100]. There is a synergistic effect between senses, positive senses increase the evaluation of other senses and negative sensory stimuli decrease the evaluation of other senses [101][102], which is a masking effect, that is also present in other sensory interactions [103][104]. Visual interference affects humans' sound pleasure, and perception of the soundscape may vary depending on the combination of landscapes and sounds. Therefore, the effects of noise generated in urban spaces can be counteracted to some extent by the inclusion of pleasurable visual elements.

This study also used the PRSS scale for audiovisual stimuli, and the three types of forests, oceans, and starry skies received much higher ratings than the other three types, showing consistency with physiological indicators. In addition, SCL, HR, LF, LF/HF, SDNN, and RF had low correlations with subjective ratings, suggesting that the relationship between these six indicators and recovery assessment factors may be weak.

4.3. Limitations and further research

The following limitations exist in this study. In terms of subjects selection, the study was conducted with participants in the younger age group (20 ~ 25 years old), which poses the challenge of applying the findings to other age groups. This study investigated the outcomes of short-term stimulation on participants, suggesting that more experiments are needed to obtain the long-term recovery effects of continued exposure to stimulation interventions. This study only explored the effects of the three stimulation modalities, suggesting that there is a need to investigate the recovery benefits of more sensory interactions [105][94], and furthermore, the introduction of deep learning would better identify participant states [106]. In our study, we chose material that had consistency between sound and video semantics, inconsistency is worth exploring in future research. The present study simulated an indoor environment in a residential area, a non-work condition. In other places, such as offices, schools, etc., participants' behaviors and

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responses may be different due to the different tasks and conditions, which need to be further explored by corresponding experimental designs. In addition, participants' emotions can be assessed more accurately by choosing semantic words. Despite these limitations, this study achieved the following: 1) compared the recovery effects of the six scenes in terms of three stimulus modalities, and 2) used a preference scale to obtain associations with physiological indexes of recovery, and explored a certain law of action between the senses.

5. Conclusion

This study examined 6 soundscape scenes and compared participants' short-term physiological responses and subjective evaluations under 3 stimulus modalities in these environments. This research explored the relationship between different stimulus modalities and scene types with physiological recovery and participants' subjective preferences. This provides design guidelines for healthy indoor soundscape environments for urban residents, and the findings are as follows:

- (1) Comparing the 3 stimulus modalities, the 4 metrics of TBR, RD, R-value, and mean pupil diameter showed that audiovisual stimulation led to better retention of attention and moderate arousal of the participants, and had a more stable and better recovery and that the visual element and the auditory element caused a lesser effect than the audiovisual stimulation on the human body. In urban scenes, single visual stimuli are superior to single auditory stimuli, influenced by sensory prioritization and masking. In addition, physiological correlation studies have found that audiovisual stimulation activates more physiological changes, cardiac changes are highly sensitive and holistic, and the intensity of a single visual stimulus is greater than that of a single auditory stimulus.
- (2) Comparing the 6 scene types, the forest, ocean, and starry sky scenes showed stronger physiological recovery in PNN50, HF, and LF/HF metrics; the results of the audiovisual stimulation showed a stronger consistency than that of the visual and auditory. There was no obvious pattern in the change of the RF and the average pupil diameter metrics. Subjective preference was dominated by the scene type, with a low correlation with stimulus modality. The audiovisual and auditory stimuli frequency scores were slightly higher than the visual stimuli in the highly rated scenes.
- (3) In terms of the soundscape PRSS evaluation, there was a strong correlation between physiological indicators and subjective ratings for audiovisual stimuli, with high scores for forest, ocean, and starry sky types, which were more in line with subjects' recovery needs. Due to prior experience bias, the preference scores of the five dimensions of the city were lower than those of the other five types of scenes. The low scores of the 2 types of scenes, grassland, and desert, were mainly caused by the results of the subjects' low familiarity.

Data availability

Data will be made available on request.

Declaration of competing interest

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.

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CRedit authorship contribution statement

Chengmin Zhou: Conceptualization, Methodology, Validation, Writing - review and editing, Funding acquisition, Supervision, Project administration. **Binhui Xu:** Data curation, Methodology, Formal analysis, Writing – original draft, Visualisation, and Software. **Xue Xu:** Formal analysis, Investigation, Visualisation, Writing—original draft. **Jake Kaner:** Writing—review and editing, Funding acquisition.

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A. Appendix-Stimulus material content

This study explores the application of presenting exterior soundscapes in indoor spaces. Nature has been shown to have good restorative benefits, so the soundscapes chosen include 1) natural soundscapes: forests, oceans, deserts, and grasslands. and 2) man-made soundscapes: starry sky and urban. Due to the similarity of urban soundscapes [107], vehicular traffic was then chosen as an example. The six stimulus materials were selected from open sources based on certain criteria, which were as follows: (1) Literature research: soundscapes used in existing literature studies that have research value [108][109]. (2) Expert review: Experts initially screened each material for screen changes and elemental composition to ensure the integrity of the material. Then use Adobe Premiere Pro 2020 software to edit into a 1-minute video, smooth video images, a macro scene and changes, to ensure that the 4K resolution (3840 * 2160 pixels). The visual stimuli were displayed on an HP monitor with Windows 10 Professional operating system and a resolution of 1680*1050. Meanwhile, in the experimental environment, a portable sound level meter (GT13556, frequency response: 31.5 Hz ~ 8.5 kHz, accuracy: ± 1.5 dB) was used to measure the equivalent continuous A-weighted sound pressure level, ensuring that the sound environment was controlled to 30 dB ~ 34 dB in a quiet state. When audio was played, the sound pressure level was continuously measured, and then adjusted using the volume keys. After repeated calibration, the sound source was controlled to play sounds within the range of 35 dB ~ 45 dB. The sound in this range is described as normal as well as lower conversational sounds, with an overall comfortable and stable. Each scene played 1 minute (1 minute of video with sound, 1 minute of video without sound, 1 minute of audio), a total of 18 scenes. The sounds were played by wireless stereo equipment placed 30 cm away from both sides of the subjects' bodies in the laboratory. Subjects faced a white screen in single auditory experiments. (3) Questionnaire validation: A questionnaire survey was conducted on 40 urban residents, which was used to determine the reasonableness of the scenes.

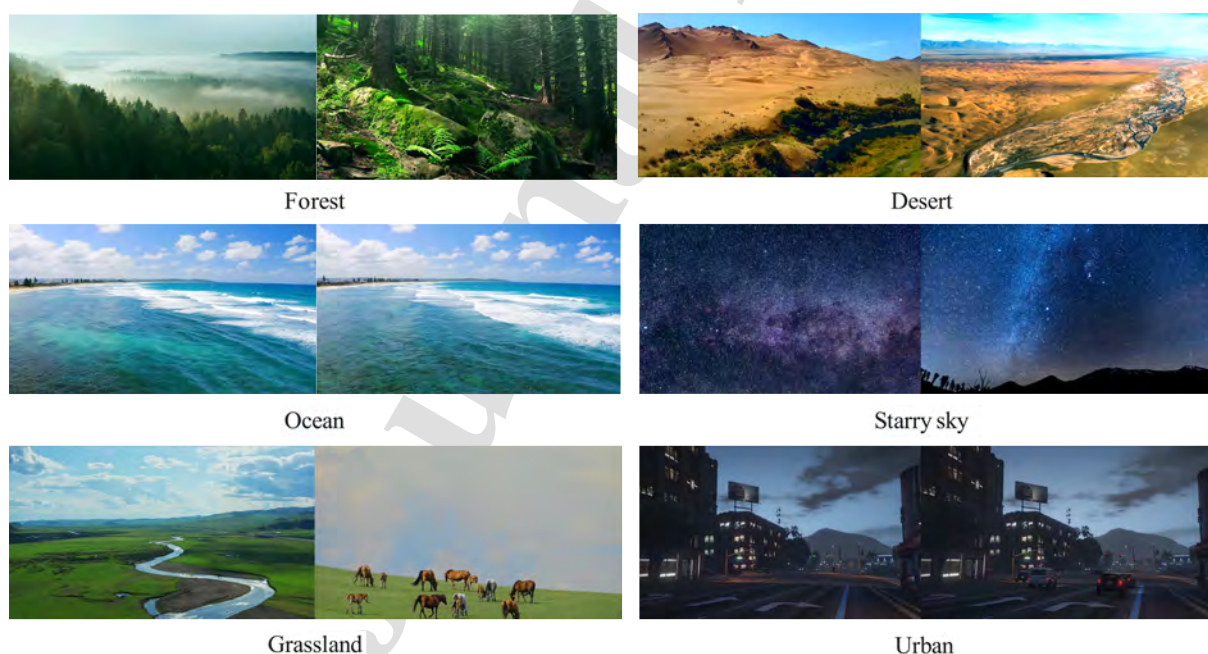


Figure 12: Partial presentation of soundscape video

Regarding landscape, the content included 1) natural landscapes with their respective semantic characterization elements, and 2) landscapes with man-made elements. Regarding sound, the content includes 1) sound generated by the

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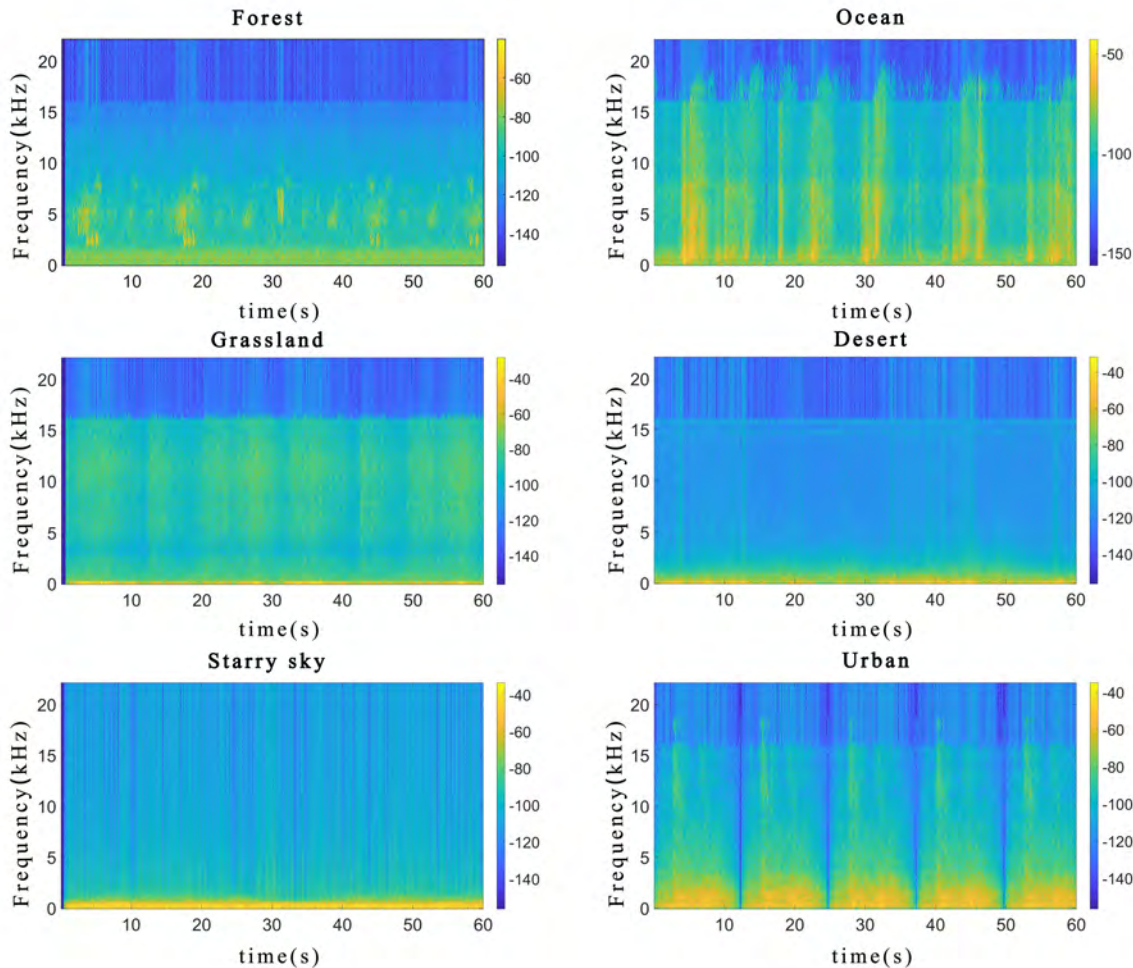


Figure 13: Audio Material Spectrogram

natural area itself, and 2) sound associated with man-made elements (e.g. traffic sound). For the starry sky soundscape materials, images containing starry sky elements and alpha brainwave music were selected. Forest: A natural forest at sunrise with hazy fog, with birds moving around and leaves fluttering [110]. Ocean: A beach and waves on a sunny and unattended day, with the waves surging with the time of day. Grassland: Green plains with streams, wide vistas, and an abundance of animal activity. Desert: An open desert landscape with a yellowish-brown body, which includes elements such as sand, dead wood, rocks, and part of an oasis. Starry Sky: An extraordinary landscape with a blue-violet night sky, with stars as the main elements that twinkle and change over time. Urban: An intersection with many vehicles driving in the evening, vehicles moving according to the traffic light changes, surrounded by a forest of tall buildings. As shown in Fig 12.

The sound material is semantically identical to the visual material. The sounds in the forest include elements such as birdsong, insects chirping, running water, and are smooth and continuous. The sounds of the ocean include the waves crashing and lapping on the beach, with a few abrupt changes in sound. The sounds of the grassland include the sound of running water, wind, and animal calls, and are smooth and peaceful. The sounds of the desert are dominated by the sound of the wind, with very little variation. Starry sky sounds are alpha brainwave music and contain no elements. Urban sounds include the sound of vehicles traveling with more noticeable abrupt changes in sound. Humans can reconstruct consistent similarity relationships between soundscapes [111]. Studying these soundscapes is highly relevant and practical. As shown in Fig 13.

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Table 4

Test results of construct validity

Reliability analysis		KMO and Bartlett test		
Cronbach's alpha	number of terms	KMO sample appropriateness measure		0.745
0.776	6	Bartlett's test of sphericity	df	15
			p	0.000**

Note: ** denotes $p < 0.005$, indicating significance between data.**Table 5**

Survey data statistics

Soundscape type	Pleasure	Arousal	Dominance	Authenticity	Acceptance	Familiarity
1 Forest	3.15 (1.48)	2.88 (1.04)	4.15 (0.98)	3.38 (1.19)	4.05 (1.13)	2.83 (1.39)
2 Ocean	2.93 (1.37)	2.87 (0.94)	4.23 (1.00)	3.60 (1.41)	4.10 (0.90)	2.95 (1.43)
3 Grassland	3.13 (1.52)	2.88 (0.97)	4.08 (1.05)	3.39 (1.41)	3.85 (1.08)	3.15 (1.31)
4 Desert	3.05 (1.40)	3.03 (1.23)	4.15 (1.14)	3.37 (1.33)	2.90 (1.45)	3.08 (1.38)
5 Starry Sky	3.08 (1.49)	3.05 (1.13)	3.88 (1.26)	3.58 (1.34)	4.03 (1.05)	3.20 (1.32)
6 Urban	3.18 (1.53)	2.85 (1.05)	1.75 (0.87)	3.53 (1.36)	2.95 (1.14)	4.38 (0.77)

B. Appendix-Reliability test and statistical analysis of the questionnaire

A questionnaire was administered containing six scenes before the experiment, and the questionnaire topics included pleasure, arousal [112], dominance, authenticity, acceptance, and familiarity in the form of a five-point Likert scale. A total of 40 valid questionnaires were collected and tested for reliability and validity. The Cronbach's alpha coefficient value of the data model was 0.776, and when the coefficient value reached or exceeded 0.7, the scale was considered to have good reliability. The results of the validity analysis of the data indicated that KMO values > 0.7 and Bartlett's test of sphericity ($p < 0.005$) were both significant at the data level, indicating that there was a correlation between the variables and that the factor analysis was valid at the appropriate level. As shown in Table 4.

The results of the questionnaire are shown in Table 5. The pleasure and arousal of materials indexes did not differ much, and the participants' ratings were all around 3, indicating that they were satisfied with the material. The authenticity scores of the materials were all greater than 3.3, indicating that the materials were consistent with the real environment and had a sense of real experience as stimulus materials. This means that the participants were able to easily understand and recognize what the stimulus material conveyed. The results of the acceptance index were similar to those of the dominance index, indicating that they were more accepting of soundscapes that they could control. In the familiarity index, the urban scene was more familiar than the other scenes, which also rated close to 3 and also within the participants' perceptions. Although the dominance of the urban scene was lower, we still chose this scene as a stimulus scene because the urban scene is universal and fits our modern living space, and we would like to explore the design direction of this scene through subsequent research.

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C. Appendix-Statistical results and significance test of TBR data

Table 6: TBR result statistics

Channel	Stimulus Modality	Number of cases	mean value	standard deviation	standard error	The 95% confidence interval for the mean	
						Lower limit	superior limit
Fz	A	120	-0.545	1.993	0.182	-0.905	-0.185
	B	120	0.891	3.004	0.274	0.348	1.434
	C	120	0.258	3.267	0.298	-0.332	0.849
F3	A	120	-0.953	2.219	0.203	-1.354	-0.552
	B	120	0.761	3.527	0.322	0.124	1.399
	C	120	-0.042	4.076	0.372	-0.779	0.694
F4	A	120	-0.499	2.546	0.232	-0.960	-0.039
	B	120	1.077	3.393	0.310	0.464	1.691
	C	120	-0.255	3.796	0.347	-0.941	0.431
F7	A	120	-0.856	2.584	0.236	-1.323	-0.389
	B	120	0.479	3.448	0.315	-0.144	1.102
	C	120	-0.218	3.748	0.342	-0.896	0.459
F8	A	120	-0.479	2.519	0.230	-0.935	-0.024
	B	120	0.964	3.369	0.308	0.355	1.573
	C	120	-0.339	3.901	0.356	-1.045	0.366
Cz	A	120	-0.812	2.169	0.198	-1.204	-0.420
	B	120	0.185	3.064	0.280	-0.369	0.739
	C	120	0.104	3.302	0.301	-0.493	0.701
C3	A	120	-1.25	2.623	0.239	-1.724	-0.776
	B	120	0.449	3.570	0.326	-0.197	1.094
	C	120	0.115	3.975	0.363	-0.604	0.833
C4	A	120	-0.852	2.333	0.213	-1.274	-0.430
	B	120	0.487	3.337	0.305	-0.116	1.091
	C	120	-0.160	3.644	0.333	-0.819	0.499
Pz	A	120	-0.600	2.487	0.227	-1.049	-0.150
	B	120	0.127	3.377	0.308	-0.484	0.737
	C	120	-0.261	3.242	0.296	-0.847	0.325
P3	A	120	-1.211	2.648	0.242	-1.689	-0.732
	B	120	0.493	3.240	0.296	-0.093	1.079
	C	120	-0.186	3.631	0.331	-0.843	0.470
P4	A	120	-0.737	2.389	0.218	-1.169	-0.305
	B	120	0.385	3.359	0.307	-0.223	0.992
	C	120	-0.500	3.413	0.312	-1.117	0.117
O1	A	120	-0.408	3.040	0.278	-0.957	0.142
	B	120	0.434	3.662	0.334	-0.228	1.096
	C	120	-0.661	3.575	0.326	-1.307	-0.015
O2	A	120	-0.676	3.606	0.329	-1.328	-0.025
	B	120	0.568	3.210	0.293	-0.013	1.148
	C	120	-0.985	3.188	0.291	-1.561	-0.409

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Table 6 – Continued

Channel	Stimulus Modality	Number of cases	mean value	standard deviation	standard error	The 95% confidence interval for the mean	
						Lower limit	superior limit
Fpz	A	120	-0.025	2.884	0.263	-0.546	0.497
	B	120	0.592	3.293	0.301	-0.004	1.187
	C	120	-0.020	3.603	0.329	-0.671	0.632
P7	A	120	-1.093	3.316	0.303	-1.693	-0.494
	B	120	-0.315	3.559	0.325	-0.958	0.328
	C	120	-0.632	3.257	0.297	-1.220	-0.043
P8	A	120	-0.599	2.670	0.244	-1.082	-0.116
	B	120	0.218	3.332	0.304	-0.384	0.820
	C	120	-0.805	3.231	0.295	-1.389	-0.221

Table 7: ANOVA analysis of the three stimulus modalities in TBR groups

Channel		Sum of squares	df	Mean Square	F	p
Fz	Between-group	124.324	2	62.162	7.880	0.000*
	Within-group	2816.387	357	7.889		
F3	Between-group	176.567	2	88.284	7.796	0.000*
	Within-group	4042.587	357	11.324		
F4	Between-group	172.789	2	86.394	7.998	0.000*
	Within-group	3856.090	357	10.801		
F7	Between-group	107.03	2	53.515	4.922	0.008*
	Within-group	3881.777	357	10.873		
F8	Between-group	152.078	2	76.039	6.932	0.001*
	Within-group	3915.991	357	10.969		
Cz	Between-group	73.574	2	36.787	4.415	0.013*
	Within-group	2974.745	357	8.333		
C3	Between-group	194.394	2	97.197	8.231	0.000*
	Within-group	4215.915	357	11.809		
C4	Between-group	107.683	2	53.841	5.410	0.005*
	Within-group	3552.912	357	9.952		
Pz	Between-group	31.703	2	15.851	1.692	0.186
	Within-group	3344.004	357	9.367		
P3	Between-group	176.511	2	88.256	8.625	0.000*
	Within-group	3653.027	357	10.233		
P4	Between-group	83.895	2	41.948	4.394	0.013*
	Within-group	3408.115	357	9.547		
O1	Between-group	78.916	2	39.458	3.341	0.037*
	Within-group	4216.063	357	11.81		
O2	Between-group	162.119	2	81.059	7.265	0.001*
	Within-group	3983.294	357	11.158		
Fpz	Between-group	30.12	2	15.06	1.405	0.247

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Table 7 – Continued

Channel		Sum of squares	df	Mean Square	F	p
	Within-group	3825.467	357	10.716		
P7	Between-group	36.75	2	18.375	1.609	0.202
	Within-group	4077.826	357	11.422		
P8	Between-group	70.279	2	35.139	3.677	0.026*
	Within-group	3412.113	357	9.558		
Note: * denotes $P < 0.05$, indicating significance between data.						

(1) Audiovisual stimuli significantly leads to more stable and effective physiological recovery. However, A single sense can alleviate the effects of an uncomfortable environment.

(2) Natural scenes, particularly forests, oceans, and starry sky, demonstrate stronger physiological recovery compared to urban environments.

(3) Cardiac indicators are most closely linked to each other, and multi-sensory stimulates more physiological connections.

(4) There is a strong correlation between physiological indicators and subjective ratings for audiovisual stimuli. There is some bias between preference and physiologic recovery.

Author Statement:

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We also agree that, if accepted, the paper will not be published in any form, in English or any other language, without the written consent of the Publisher.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. She is responsible for communicating with the other authors about progress submissions of revisions and final approval of proofs.

Declaration of 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: