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Effects of different audiovisual landscapes in bamboo forest space on physical and mental restorative potential of university students: based on eye-tracking experiments

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With its unique audiovisual environment, bamboo forest spaces serve as natural sanctuaries for urban residents, offering significant restorative effects by reducing physical and mental stress and alleviating fatigue. This promotes the vigorous development of outdoor recreation activities. To further explore the restorative effects of bamboo forest space on people's audiovisual perceptual aspects. In this study, we conducted field research in the Southern Sichuan Bamboo Sea, collecting audiovisual materials from four types of bamboo forest spaces: pathway type, cultural type, ornamental type, and recreational. These spatial photographs were combined with three types of soundscapes (silent, background, and background + wind-blown bamboo sound). Eye tracking experiments were utilized to investigate the physical and mental restorative effects of these different audiovisual features on college students. The results showed that in the visual aspect, the visual restorative properties of recreational-type and ornamental-type bamboo spaces were better than those of pathway type and cultural-type spaces; in the auditory aspect, the sounds of wind-blown bamboo, flowing water, and chirping birds in the bamboo forest significantly enhanced the subjective restorative properties of the bamboo forest space, reducing the number of fixations and the average pupil diameter. In addition, this paper found that the soundscape guided people's visual attention, with the wind-blown bamboo sound increasing focus on natural elements, and the extensibility of the bamboo forest space was positively correlated with the number of fixations, while fascination was negatively correlated with the average saccade amplitude. These findings provide insights for the optimized design of audiovisual restorative environments in bamboo forest space in the future.

KEYWORDS
bamboo forest landscape, environmental restorative, eye-tracking indicators, audiovisual interaction, physiological and psychological parameters

1 Introduction

Currently, with the growth of the urban residential population and fast-paced work and lifestyle, people of all ages are subjected to increasing social pressure (Šabanović et al., 2020). Such stress not only negatively affects the physical and mental health of individuals, such as emotional anxiety and distraction, which are gradually becoming more prominent (Li et al., 2024), but also poses a potential threat to the overall productivity and wellbeing of society (Gong, 2023). Studies have shown that natural environments have significant healing effects on human physical and mental health (Larson and Hipp, 2022). For example, viewing forested landscapes significantly increases parasympathetic nervous activity and decreases sympathetic nervous activity and heart rate in young women (Chorong et al., 2019). In order to further explore the restorative mechanisms of the environment for humans to better enhance the healing properties of the environment, scholars have conducted research on the visual, auditory, olfactory, and other dimensions of the environment (Gao et al., 2020; Liu et al., 2022). Visual perception is considered to be one of the important dimensions of human perception of the external environment. It has been found that different spatial types, elemental compositions, and the way they are laid out can significantly affect the restorative properties of the environment (Zhao et al., 2020; Shu et al., 2022). For example, visual elements such as open vistas, abundant green vegetation, and harmonious color schemes tend to trigger positive emotional responses and promote physical and mental restorative qualities (Akers et al., 2023; Liu et al., 2023). However, it is worth noting that visual perception, although dominant in information acquisition, is not always the primary factor influencing the final perceptual outcome. In some cases, soundscape perception can also be the key to influencing the overall environment perception (Hong et al., 2022). For example, Zhu et al. (2020) showed that natural soundscapes, such as birdsong, not only enhance the psychological healing effect of park environments but also interact with visual elements to enhance the overall restorative effect of the environment. Therefore, audiovisual perception is the main form of people's cognition of the environment, and synthesizing the interaction of vision and hearing can produce a more complete understanding of the site.

The restorative effects of the environment on people are mainly manifested in physiological and psychological changes, and the data are usually quantitatively summarized in research using both subjective and objective dimensions. Hartig et al. (1996) developed the first restorative environment questionnaire, the Perceived Restorativeness Scale (PRS), based on the theory of attentional restoration in 1996. Since then, scholars have continuously improved and optimized the questionnaire content for different environmental characteristics, forming various questionnaires such as the Restorative Components Scale (RCS). Eye-tracking technology is a commonly used research tool in psychological experiments, in which researchers often use eye-trackers to record the eye movement trajectories of subjects while viewing test stimuli and then quantify and analyze the eye movement data, such as gaze, eye hopping, and follow-through through eye-movement analysis software, to obtain the subject's visual cognitive patterns (Liu et al., 2022; Prasse et al., 2024).

With the advent of optical methods, eye-tracking techniques have become simplified and matured, resulting in a wealth of research results. Compared with other physiological monitoring methods, such as EEG signals that respond to the relaxed and tense state of the brain by monitoring alpha and beta waves, and skin electrical induction signals that respond to transient fluctuations in mood by monitoring changes in the skin's electrical conductivity, eye-tracking techniques capture the most primitive physiological data, including those without active consciousness (Wang et al., 2021, 2024). This makes eye-tracking an effective tool for exploring the physiological effects of the human body.

The integration and processing of transient data to generate heat maps and trajectory maps can visualize the attractiveness of different landscapes (Martínez-Soto et al., 2019). Metrics such as the number of fixations, the number of saccades, and the average pupil diameter are significantly correlated with the attractiveness of the environment and the human cognitive response to it (Gao et al., 2020). Li et al. (2022) showed that the number of fixations and average pupil diameter were significantly lower when viewing a rural nature scene compared to an urban scene, demonstrating a high degree of restorability. Thus, exploring changes in eye movement indicators provides new insights for restorative research in audiovisual environments.

China is the richest country in the world in terms of bamboo resources, and bamboo forests hold high economic and cultural values (Xu et al., 2023). Studies have shown that bamboo is a fast-growing, highly carbon-absorbing plant, and living bamboo leaves release organic components such as terpenes and alcohol compounds, which have recreational and healthcare benefits (Farias et al., 2024). In recent years, bamboo forest recreation tourism has become an emerging tourism industry that has received increasing attention and favor (You et al., 2022).

In bamboo forest spaces, different combinations of bamboo forest and other landscape elements create distinctive visual characteristics, while the rustling sound of the wind blowing through the bamboo forest provides a unique auditory experience. Thus, the bamboo forest space itself possesses high restorative potential, making the study of its audiovisual restorative benefits highly valuable. Therefore, this study focuses on audiovisual perception, directs research toward environmental restorative benefits, and uses bamboo forest space as the research object to explore its physiological and psychological effects through eye movement analysis technology. The goal is to provide a reference for shaping and optimizing restorative environments in bamboo forest spaces. This study poses the following four questions:

(1) Do different types of bamboo forest spaces affect human physiological and psychological effects differently?
(2) What are the differences in restorative effects of each audiovisual feature on bamboo forest space and their visualization results?
(3) Does the sound of wind blowing in the bamboo forest help to enhance the physical and mental restorative effects of the bamboo forest space on people?
(4) What relationships exist between the restorative potential of bamboo forest space and eye movement indicators?

2 Materials and methods

2.1 Study area and photographs

In this study, field photos and sounds of bamboo forest landscapes were used as materials for eye movement experiments.

Numerous studies have shown that pictures and videos can be used instead of real environments when studying the effects of different landscape scenes on people and that there is a high degree of similarity between the physiological and psychological effects of the two (Berman et al., 2009; Li et al., 2021). The sampling site was chosen to be located in the Southern Sichuan Bamboo Sea Scenic Spot in Yibin City, Sichuan Province, China. This scenic area has the largest concentrated area of natural bamboo forest scenic area in the world. It skillfully integrates bamboo forests with lakes, ancient temples, waterfalls, rock walls, and other landscape elements, which is typical and representative of the spatial study of bamboo forests.

Before conducting field photography, the bamboo forest space was categorized by combining the basis of forest space classification and the structure and function of the existing bamboo forest space. According to the existing research, the common structure of forest space includes three types of forest interior space, forest path space, and forest exterior space (Lin et al., 2020), and the main functions of bamboo forest space include access, culture, viewing, and rest (Chen et al., 2014; Tsuyoshi et al., 2015; Rathour et al., 2022). Therefore, the bamboo forest space can be divided into four types: "pathway type," "cultural type," "ornamental type," and "recreational type," which reflect the audiovisual restoration characteristics of the bamboo forest space from the perspective of tourists' experience. Among them, the pathway-type bamboo space is mainly for passage function, there is a passage corridor shuttling in the bamboo forest, the environment is quiet and tranquil, occasionally there are a few sounds of insects, the landscape style is more homogeneous and unified; cultural-type bamboo space has an obvious cultural atmosphere, this study chooses the traditional temple culture as a representative of cultural elements, the space can be heard in the obvious sound of the ancient bells and religious music; ornamental-type bamboo space is mainly for viewing function, there is an obvious visual focus, this study considers the bamboo water flow elements as the focus of the landscape, and the sound of water flow becomes the dominant sound in the space; recreational-type bamboo space is mainly for leisure atmosphere, the exterior is surrounded by the bamboo forest, the interior view has a certain degree of openness, surrounded by recreational structures, the space can be heard from time to time a few birdsong.

Based on the above categorization, this study was conducted in March 2023 in the core bamboo viewing area of the Southern Sichuan Bamboo Sea, choosing a sunny, haze-free time from 9 a.m. to 5 p.m. with a wind speed of <5 m/s for sampling audiovisual elements. A Nikon camera (NIKON D7000, Japan) was used for live photography, a ZOOM stereo multi-track recorder (ZOOH H5, Japan) with a Rhodes directional microphone (Video Mic NTG, Australia) was used for simultaneous sound recording, and an AWA sound level meter (AWA-5636, China) was used to measure the sound pressure level at each recording point. The height of the equipment was kept at 1.5 meters, and the duration of sound recording, and sound level measurement was 5 min. A final total of 12 pathway spaces, eight cultural spaces, 10 ornamental spaces, and eight recreational spaces were collected in photographs and audio. Three qualified landscape architects selected the most representative material scenes for each bamboo forest type from these, using the quality of the audiovisual scenes and the wide range of variability of each space as criteria (Figure 1).

2.2 Production of audiovisual stimuli

The audio files of each scene were edited into 30-s segments using Premiere software (Adobe Systems Pro 2020, USA). The volume was calibrated so that the background sound signals in all four spaces were close to the measured sound pressure level (LAeq) (Table 1), which was used as the background sound material (S1–S4). A 30-s silent audio file (S0) was generated to explore the restorative role of soundscape in the bamboo forest space by comparing the changes in physiological and psychological indicators of people in silent and background sound scenes. In order to explore the role of a unique soundscape in the bamboo forest space, the wind-blown bamboo sound, the study also added the separately recorded wind-blown bamboo sound to the background sound basis of each space (in order to avoid the influence of the wind factor in the environment on the experimental samples, the environmental sound collected in the field was selected when the wind force was <5 m/s, so the wind-blown bamboo sound was not included in the background sound), forming a composite audio clip consisting of 50% ambient sound and 50% bamboo sound (S1 + S5–S4 + S5). Finally, the four types of bamboo forest spaces were combined with three types of audios to form three types of the silent sound group, the background sound group, and the background sound + wind-blown bamboo sound group, totaling 12 different bamboo forest audiovisual scenes (Figure 1).

2.3 Subjects

Past research has shown that college students can serve as ideal experimental subjects in lieu of the general population, with no significant differences between their results and those of the general population (Yao et al., 2012). Meanwhile, on the basis of the pre-experiment, the efficacy analysis of G*Power 3.1.9.7 software (G*Power, Germany) was utilized to calculate the sample size used in the study (Meng et al., 2020) (preset Effect size $f = 0.25$, $d = 0.50$, significance level $\alpha = 0.05$, and power = 0.8), and the results indicated that at least 24 subjects were needed in each group. In order to facilitate the grouping, this study finally recruited 32 current college students from Sichuan Agricultural University to participate in the experiment, and the summoned students fulfilled the following characteristics: (1) normal visual acuity, with naked eye or corrected visual acuity at the level of 5.0 and above, and no other vision problems; (2) no hearing impairment, no reading or cognitive impairment; and (3) recent physical condition, and no bad habits such as alcohol abuse, smoking, and so on.

2.4 Evaluation scales and measures

2.4.1 Eye movement indicators

The eye-tracking device for this study was the Tobii Pro Glasses 2 wearable eye-tracker, which integrates an

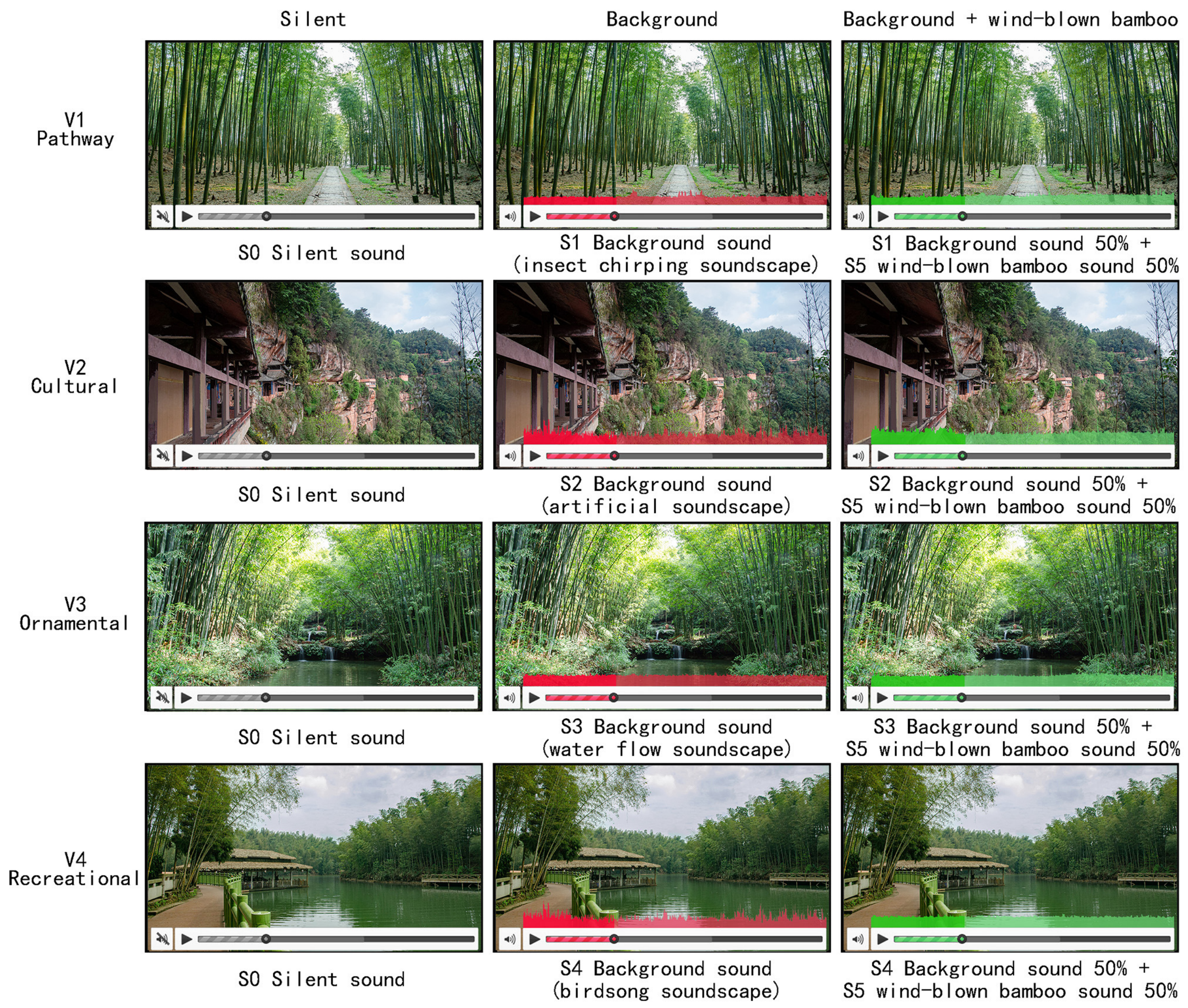

FIGURE 1
Audiovisual stimulus materials. V1, pathway-type bamboo space; V2, cultural-type bamboo space; V3, ornamental-type bamboo space; V4, recreational-type bamboo space; S0, silent scene; S1-S4, background scene; S5, background + bamboo forest sound scene.

TABLE 1 Analysis table of each auditory and physical feature in each spatial picture of bamboo forests (unit: dB).

Type	LAmin	L90	L50	L10	LAmax	LAeq
Pathway space	30.0	30.9	32.9	36.1	43.0	34.1
Cultural space	43.0	43.2	43.7	46.8	65.9	51.1
Ornamental space	50.1	51.0	52.8	54.7	56.3	53.1
Recreational space	33.2	33.6	34.3	36.9	38.8	35.1

LAmin, minimum sound pressure level; L90-L10, accumulated percentage sound level; LAmax, maximum sound pressure level; LAeq, equivalent continuous A-weighted sound pressure level.

eye-tracking system and a scene camera on a lightweight frame and measures eye movements at a sampling rate of 100 Hz in the form of viewing through glasses. The audiovisual scene of the experiment was presented through a 15.6-inch computer (Dell Inspiron 7577, China) with a resolution of 1,920 × 1,080 pixels. Five metrics, average fixation duration (AFD), number of fixations (NoF), average saccade amplitude (ASA), number of saccades (NoS), and average fixation pupil diameter (APD), were selected for eye movement analysis.

2.4.2 Indicators for subjective restorative evaluation

The Short-version Restorative Components Scale (SRCS) was selected for subjective restorative evaluation. The scale was derived from the Restorative Components Scale (RCS) developed by Laumann et al. (2001). The four characteristics that restorative environments should have: remoteness, extensibility, fascination, and compatibility were used as the basis for evaluating the dimensions in order to assess people's subjective restorative perceptions of the environment. In order to avoid the interference of eye-tracking data by filling out the questionnaire for a long period of time, a topic suitable for the spatial evaluation of bamboo forests was selected from each dimension as a modified short questionnaire (Han, 2003). According to the application of related studies and the results of the pre-experiment, it can be seen that the censored scale still meets the statistical requirements and does not make a significant difference to the experimental results (Deng et al., 2020; Fu et al., 2022). The SRCS scale, as shown in Appendix A, consists of four questions that are scored on a seven-point scale (one for strongly disagree and seven for strongly agree).

2.5 Experimental procedures

To ensure a multifactorial and controllable experimental environment, the experiment was conducted in a quiet and clean laboratory with a room temperature of 25 ± 2°C, a humidity of 72 ± 5%, and a background sound level of <25 dB during the experimental period. The experimental times were all controlled to be between the periods of 9:00–11:00 a.m. and 2:00–5:00 p.m. to eliminate the effects of circadian variations in physiological rhythms. Each participant was required to wear a Tobii Pro Glasses 2 wearable eye-tracker and Sony noise-canceling headphones (Sony MDR-XB950N1, Japan) to view 12 audiovisual scenes, all of which were presented using a 15.6-inch Dell computer (Dell Inspiron 15-7577, USA). A total of 32 subjects were randomly assigned into four groups, each with an equal proportion of men and women (containing four men and four women), to eliminate the sequence difference generated by the within-group design (Figure 2), and the specific experimental procedure consisted of four phases.

Before the start of the experiment, the staff first briefly explained the precautions and process details of the experiment to the subjects and then calibrated the eye-tracking device to ensure that the eye-tracking data were obtained with a high degree of accuracy. The experimental scene recovery experience was divided into three parts: the first part was a four-stimulus group with silent sound, the second part was a four-stimulus group with background sound, and the third part was a four-stimulus set of background sounds + wind-blown bamboo sounds to simulate a scene in a bamboo forest where the wind is blowing. Each stimulus group was experienced consecutively for 30 s, with a 30 s interval between two stimuli (Deng et al., 2020; Fu et al., 2022). During the interval, subjects were asked to rate the restorative perception factor (SRCS) of the previous scene. After the completion of one part, subjects took a 1-min break and repeated the above steps to experience the next part of the scene (Figure 3). The entire experience lasted about 15 min, and at the end, subjects assessed the immersion of the experiment on an 11-point linear scale (scoring from −5 "I didn't feel immersed at all" to 5 "I felt immersed at all"), and each participant was paid 30 RMB at the end of the experiment.

2.6 Data analysis

In this experiment, we chose gaze samples >70% of the eye movement data as valid data, and the sampling rate of 2 subjects in the experiment finally did not meet the requirements, so the final valid data of the experiment was 30 (including 16 males and 14 females), and the validity rate of the experiment was 93.75%, which meets the statistical requirements. The mean value of the subjects' immersion score for the experiment was 3.28, indicating that the overall experience of the subjects was good and the results of the experiment were reliable and authentic.

For statistical analysis of the data, all questionnaires were tested for reliability and validity, and the results showed that all data were reliable (Cronbach's $\alpha > 0.7$, KMO > 0.6, $P < 0.05$ in the Bartlett Test of Sphericity). Physiological and psychological data were analyzed and processed using SPSS 24.0 software (SPSS, Chicago, IL, USA), and a P value of <0.05 indicated statistical significance. Repeated measures ANOVA was used to explore the physiological and psychological effects of visual and auditory factors on human beings, respectively, and to further validate the variability between each factor. Finally, correlation analyses were used to explore the effects between eye movement indexes and psychological indexes.

3 Results

3.1 Comparison of subjective restorative ratings

3.1.1 Restorative scores for different visual types

In order to visually explore the differences in psychological healing properties of different bamboo forest spaces, a repeated measures ANOVA was conducted to analyze the total SRCS scores of four types of visuospatial scenes under the same type of sound, and the results showed that the subjective restorative effect was best for the recreational-type space and that this variability was significant in the silent sound ($F = 2.836$, $p = 0.043$) and background sound ($F = 4.858$, $p = 0.004$). As shown in Figure 4, when there was no sound, the total SRCS score of the recreational-type space was the highest (18.90 ± 4.82), and there was little difference in the scores of the remaining three spaces; when there was background sound, the scores of the recreational-type space (20.97 ± 4.56) and ornamental-type spaces (19.77 ± 4.81) were significantly higher than those of the pathway-type space (17.83 ± 3.95; $p < 0.05$); and when the sound of the wind-blown bamboo was added, the score of the recreational-type space remained the highest (22.57 ± 3.44), but there was no longer a significant difference between the four types of spaces. This suggests that a range of features in the open space, including regular layout, environmental coherence, and the interplay of water features and restful architecture, work together to create a comfortable environment that exhibits a high level of restorative characteristics and a good potential for psychological recovery.

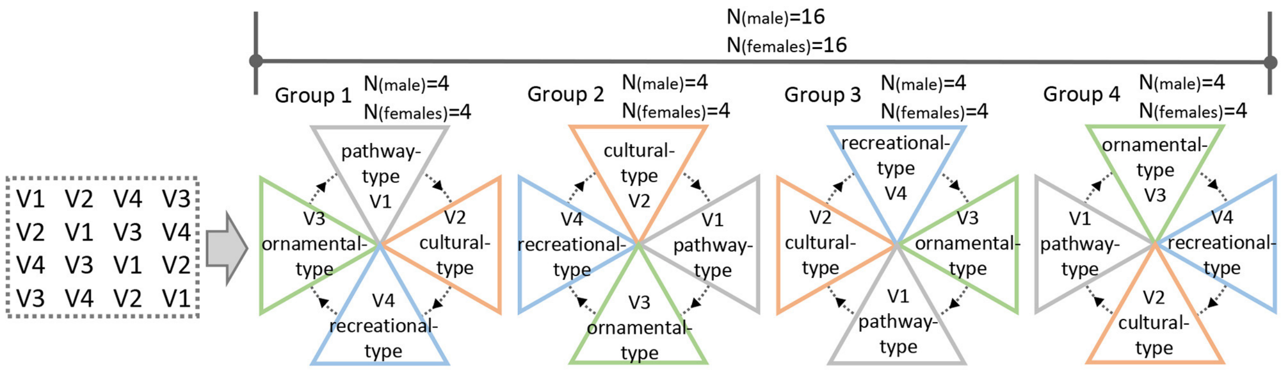

FIGURE 2
Experimental grouping and stimulus group sorting.

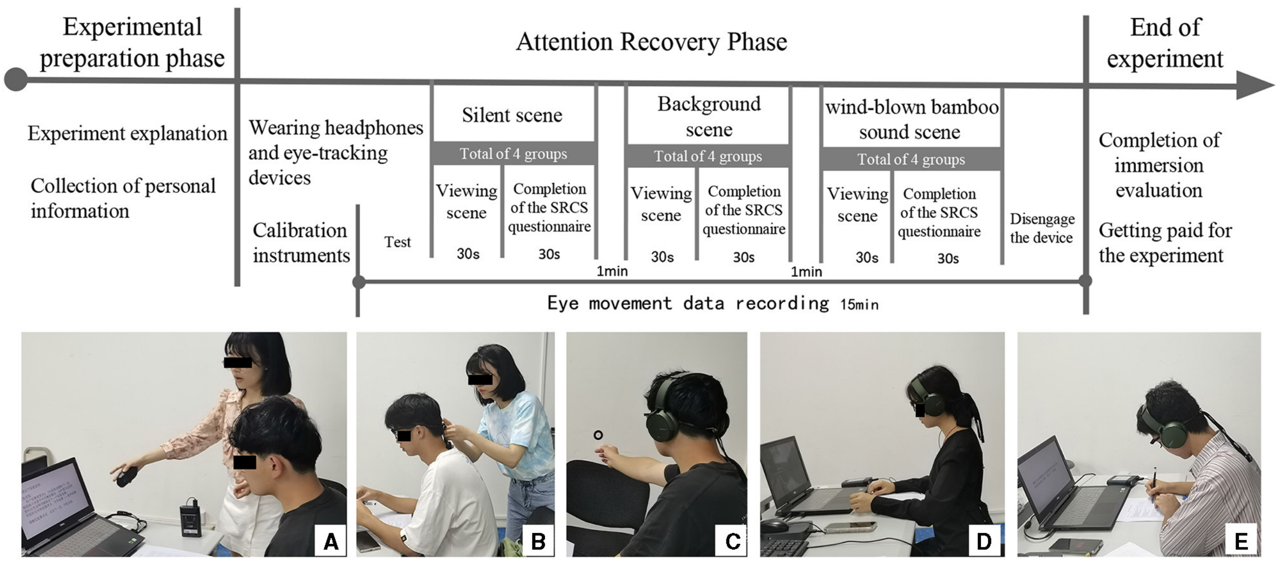

FIGURE 3
Flowchart of the experiment. **(A)** Experimental explanations; **(B)** wearing of laboratory instruments; **(C)** calibration of the oculomotor apparatus; **(D)** viewing of audiovisual scenes; and **(E)** completion of the restorative evaluation questionnaire.

3.1.2 Restorative scores for different auditory conditions

In order to aurally explore the differences in psychological restorative properties of different bamboo forest spaces, a repeated measures ANOVA was conducted on the total SRCS scores of the three types of sound conditions in the same space, and the results showed that the addition of the wind-blown bamboo sound to the background sound significantly enhanced the subjective restorative properties of the four types of bamboo forest spaces ($F_1 = 11.339$, $P_1 < 0.001$; $F_2 = 9.301$, $P_2 = 0.001$; $F_3 = 12.753$, $P_3 < 0.001$; $F_4 = 12.088$, $P_4 < 0.001$). The results, as shown in Figure 4, showed that the total SRCS scores with the addition of the bamboo forest sound were significantly higher than the scores of the no-sound scenes in all four spaces ($p < 0.01$), and the scores were also significantly higher than those of the background-sound scenes in the three spaces, except for the ornamental-type space ($P_1 = 0.001$; $P_2 = 0.028$; $P_4 = 0.031$). In addition, the total SRCS scores for the remaining three spaces, except for the pathway-type space, were significantly higher for the background sound than for the silent scene ($P_2 = 0.014$; $P_3 = 0.001$; $P_4 = 0.011$). This suggests that soundscapes enhance the subjective restorability of a scene compared to viewing a single image and that there are significant differences in the extent to which different types of soundscapes enhance the restorability of the bamboo forest space.

3.2 Eye movement data visualization

Using Tobii Pro Lab software, 30 valid eye movement data were superimposed and processed, and the subjects' degree of gaze on the images were coded into three different color intensities, red, yellow, and green, from more to less, to generate the eye movement

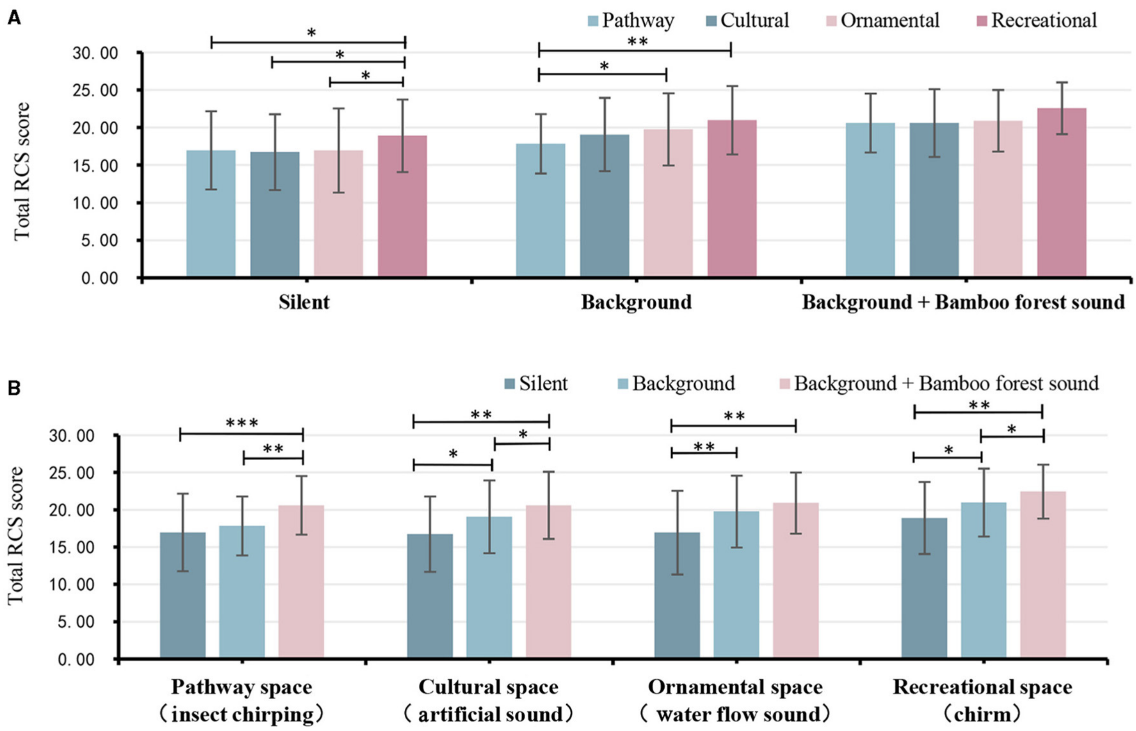

FIGURE 4
Table of spatial restorative scores for bamboo forests. **(A)** Comparison of spatial restorative scores of bamboo forests under different visual types. **(B)** Comparison of spatial restorative scores of bamboo forests under different sound types. $N = 30$; mean ± standard deviation; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; verified by repeated measures ANOVA. 1, pathway-type space; 2, cultural-type space; 3, ornamental-type space; 4, recreational-type space; in the background sound, the dominant sound of pathway-type space is the sound of insect chirping, the dominant sound of cultural space is the sound of artifacts, the dominant sound of ornamental space is the sound of water flow, and the dominant sound of rest space is the sound of chirm.

heat map corresponding to the audiovisual scenes (Figure 5). It can be found by analyzing the heat maps of the audiovisual scenes in different bamboo forest spaces:

For different bamboo forest spatial compositions, when the space consisted only of bamboo plants and road elements, subjects' attention was mainly focused on the bamboo forest. When the space consisted mainly of bamboo plants and artificial architectural elements, subjects' attention was more focused on the architectural elements. In contrast, when the space included bamboo plants in combination with the water feature, subjects' attention was mainly focused on the water feature, with less focus on the bamboo plant elements.

In addition, the more complex the spatial structure of the bamboo forest and the richer the colors and elements of the landscape, the broader the attention area and the wider the distribution of the subjects' attention points.

For different auditory types, comparing the heat maps of eye movements of the same spatial type in the three sound scenes, the gaze point of the silent scene was more dispersed from the center to the two sides of the radiating area. When the background sound was added, the gaze area was reduced. The gaze point was more concentrated in the center of the central core viewing area. After adding the sound of wind-blown bamboo and comparing the heat map of the background sound scene, the subject's attention to the whole scene increased in the four spaces. Their attention to the bamboo plants also increased, and their attention to the natural elements, such as the water and the sky, also increased accordingly. In addition, comparing the changes of the silent scene and the background sound scene in the same bamboo forest space also reveals that the sound of insect chirping can make subjects' eyes focus on the road element (compare Figure V1-S0 with V1-S1), the artificial sound can attract subjects' attention to focus on the constructed space (compare Figure V2-S0 with V2-S2), the sound of running water can make subjects' attention focus on the water flow (compare Figure V3-S0 with V3-S3), and the sound of birds chirping can increase subjects' attention to the sky element (compare Figure V4-S0 with V4-S4).

3.3 Comparison of objective eye movement behavior

3.3.1 Analysis of eye movement behavior of different visual types

The data of each eye movement behavior index are shown in Table 2. Repeated measures ANOVA (Table 3) on the mean values of each eye movement index in the four types of bamboo forest spaces under the same sound type showed that the number of fixations ($F_b = 5.740$, $P_b = 0.001$), the

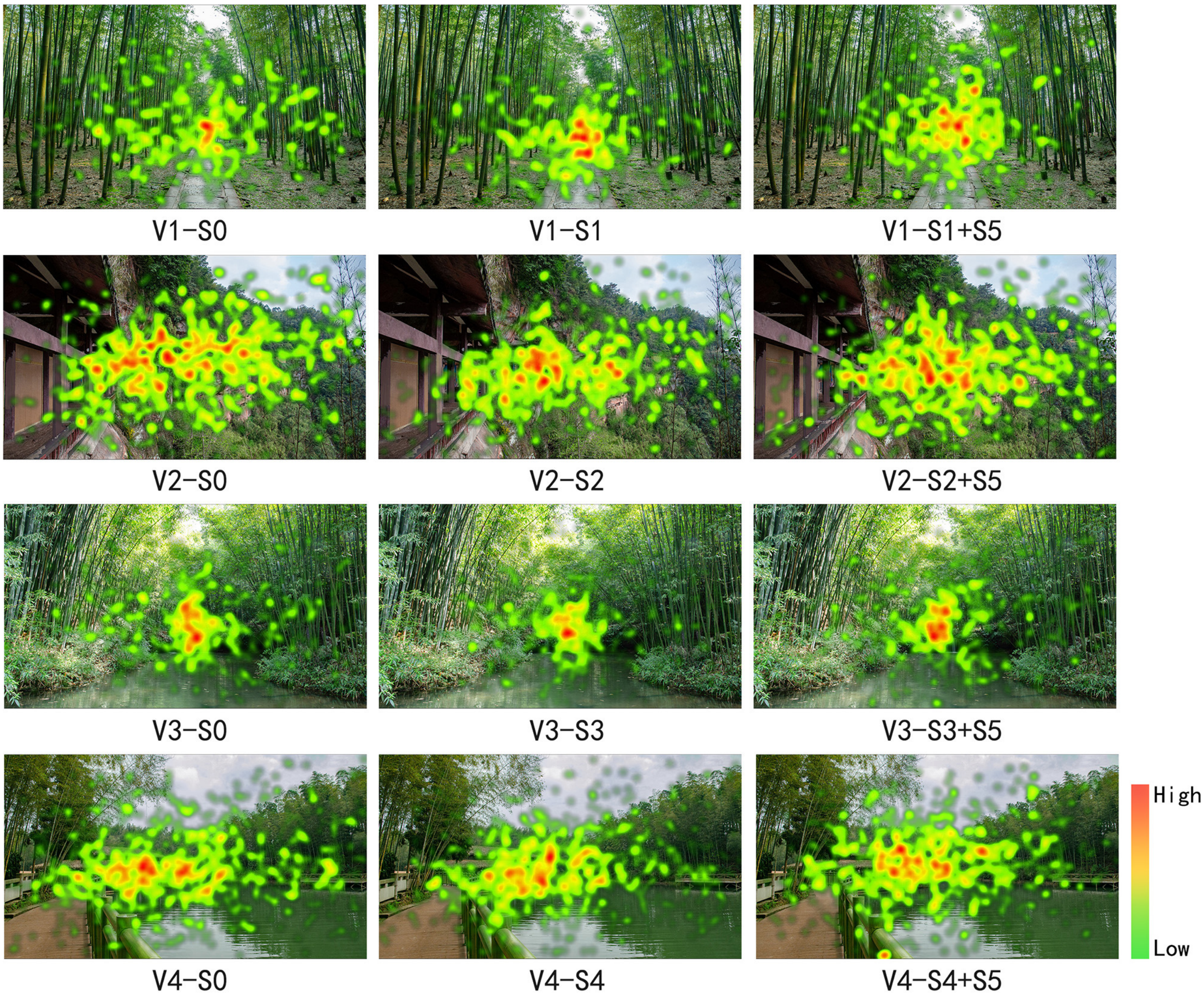

FIGURE 5
Heat map of eye movements.

number of saccades (F_b = 5.439, p_b = 0.002), and the index of the average pupil diameter (F_a = 6.838, P_a < 0.001; F_b = 3.342, P_b = 0.023; F_c = 4.201, P_c = 0.018) on the four bamboo forest spaces showed significant differences (Figure 6). The number of fixations and saccades was found to be significantly higher for the cultural-type and recreational-type spaces than for the pathway-type and ornamental-type spaces. At the same time, the average pupil diameter indicator was significantly higher for the cultural-type spaces than for the remaining three spaces.

The behavioral changes in the number of fixations and saccades were similar. For the number of fixations, cultural-type spaces (23.27 ± 13.17) and recreational-type spaces (24.10 ± 14.70) were significantly higher than pathway-type (18.03 ± 11.12) and ornamental-type spaces (18.87 ± 10.46; P_{2-1} = 0.005, P_{2-3} = 0.027, P_{4-1} = 0.004, P_{4-3} = 0.006) in the background sound scenes. Similarly, for the number of saccades, both cultural-type spaces (22.53 ± 9.59) and recreational-type spaces (23.17 ± 12.72) were significantly higher than pathway-type spaces (17.30 ± 9.77; P_{2-1} < 0.001, P_{4-1} = 0.004) in the background sound scenes.

For the average pupil diameter metric, in the silent scenes, the subjects' average pupil diameter was largest in the cultural-type spaces (4.12 ± 0.38), followed by the ornamental-type spaces (4.07 ± 0.38) and recreational-type spaces (4.06 ± 0.33), and smallest in the pathway-type spaces (3.99 ± 0.39; P_{2-1} < 0.001, P_{2-3} = 0.019, P_{2-4} = 0.034, P_{3-1} = 0.039); in the background sound scene, the average pupil diameter in the cultural-type spaces (4.07 ± 0.37) was significantly higher than in the remaining three types of spaces (p_{2-1} = 0.027, p_{2-3} = 0.014, p_{2-4} = 0.024). In the incorporation of the wind-blown bamboo sound scene, the average pupil diameter in the cultural-type space (4.00 ± 0.41) was significantly higher than that of pathway-type spaces (3.90 ± 0.42; p = 0.002) and ornamental-type spaces (3.87 ± 0.44; p = 0.016).

TABLE 2 Statistics of interval-based eye movement metrics for four types of bamboo spaces.

Type	Event number	Average fixation duration (ms)	Number of fixations (times)	Average saccade amplitude (cm)	Number of saccades (times)	Average pupil diameter (mm)
Silent	V1-S0	541.90 ± 194.29	20.80 ± 10.86	6.51 ± 1.09	20.77 ± 8.55	3.99 ± 0.39
	V2-S0	514.43 ± 197.64	24.00 ± 13.61	6.52 ± 0.97	23.23 ± 11.83	4.12 ± 0.38
	V3-S0	572.87 ± 281.55	21.60 ± 14.30	6.32 ± 1.11	21.30 ± 12.58	4.07 ± 0.38
	V4-S0	533.47 ± 255.44	24.57 ± 15.28	6.46 ± 0.98	23.03 ± 12.58	4.06 ± 0.33
Background	V1-S1	569.73 ± 262.58	18.03 ± 11.12	6.50 ± 1.16	17.30 ± 9.77	3.98 ± 0.43
	V2-S2	497.47 ± 177.25	23.27 ± 13.17	6.35 ± 1.18	22.53 ± 9.59	4.07 ± 0.37
	V3-S3	526.17 ± 220.76	18.87 ± 10.46	6.10 ± 1.12	19.57 ± 9.09	3.98 ± 0.42
	V4-S4	504.90 ± 217.35	24.10 ± 14.70	6.40 ± 1.01	23.17 ± 12.72	4.00 ± 0.35
Wind-blown bamboo sound	V1-S1 + S5	589.17 ± 355.69	19.17 ± 14.73	6.27 ± 1.20	16.63 ± 10.52	3.90 ± 0.42
	V2-S2 + S5	514.27 ± 189.20	20.30 ± 12.69	6.26 ± 1.32	20.50 ± 12.17	4.00 ± 0.41
	V3-S3 + S5	531.33 ± 297.74	18.60 ± 11.93	6.12 ± 0.95	18.27 ± 10.55	3.87 ± 0.44
	V4-S4 + S5	589.83 ± 326.48	19.13 ± 11.12	6.42 ± 1.15	18.93 ± 9.49	3.97 ± 0.42

V1, pathway-type space; V2, cultural-type space; V3, ornamental-type space; V4, recreational-type space; S1–S4, background sound; S5, wind-blown bamboo sound; mean ± standard deviation; $N = 30$.

3.3.2 Behavioral analysis of eye movements of different auditory types

Repeated measures ANOVA analysis (Table 3) of the mean values of each eye movement metric for the three auditory types in the same spatial type showed that (Figure 7) the three types of sounds exhibited significant differences in the number of fixations ($F_4 = 3.865$, $P_4 = 0.036$), the number of saccades ($F_1 = 3.741$, $P_1 = 0.030$), and the average pupil diameter metrics ($F_1 = 4.784$, $P_1 = 0.012$; $F_2 = 13.359$, $P_2 < 0.001$; $F_3 = 11.045$, $P_3 < 0.001$; $F_4 = 3.938$, $P_4 = 0.025$). It was found that the number of fixations, the number of saccades, and the average pupil diameter metrics decreased sequentially in the bamboo forest space as we moved from silent sound to background sound to the addition of the wind-blown bamboo sound scene.

For the number of fixations metrics, all four spaces showed a decreasing trend in the number of fixations in the voiced scenes. Specifically, the recreational-type space had significantly fewer fixations with the addition of wind-blown bamboo sound (24.57 ± 15.28) compared to the silent sound (24.10 ± 14.70; $P_{a-c} = 0.038$, $P_{b-c} = 0.004$) and background sound scenes (19.13 ± 11.12). For the number of saccades metric, the pathway-type space had significantly fewer saccades in the background sound (17.30 ± 9.77) and with the addition of wind-blown bamboo sound (16.63 ± 10.52) compared to the silent sound (20.77 ± 8.55; $P_{b-a} = 0.020$; $P_{c-a} = 0.009$).

For the average pupil diameter metrics, the average pupil diameter of all four spaces in the scene with the addition of wind-blown bamboo sound was smaller than that in the silent scenes ($P_1 = 0.005$, $P_2 < 0.001$, $P_3 = 0.001$, $P_4 = 0.028$), and the average pupil diameters of the other three spaces in the background sound scene were significantly lower than that in the silent scene except for pathway-type space ($P_2 = 0.001$, $P_3 = 0.021$, $P_4 = 0.037$), cultural-type and ornamental-type space were also significantly lower than that in the background sound scene ($P_2 = 0.038$, $P_3 = 0.021$, $P_4 = 0.037$), and the average pupil diameter of the cultural-type and the ornamental-type space in the wind-blown bamboo sound scene was also significantly lower than that in the background sound scene ($P_2 = 0.038$, $P_3 = 0.011$). This shows that the addition of wind-blown bamboo sound can significantly reduce the average pupil diameter metric in the bamboo forest space, and the reduction effect is more significant in combination with the insect sound, artificial sound, and water flow soundscape.

3.4 Correlation between subjective restorability and eye movement behavior

Spearman's correlation analysis of the mean values of eye movement indexes and RCS index scores of different audiovisual scenes in the bamboo forest space (Table 4) showed that the number of fixations was significantly and positively correlated with the extent index ($p = 0.021$), and the average saccade amplitude was significantly and negatively correlated with the fascination index ($p = 0.048$). It can be seen that a highly coordinated scene may trigger a more positive and pleasurable emotional response, further increasing the subjects' interest and engagement in the environment and prompting them to engage in more fixation behaviors. This may be due to the fact that the current environment is not attractive enough for the subjects who are trying to find more interesting information by scanning widely. Meanwhile, when the fascination with the environment was low, the subjects' saccade was larger. It indicates that the higher the coordination of the audiovisual environment, the higher the number of fixations.

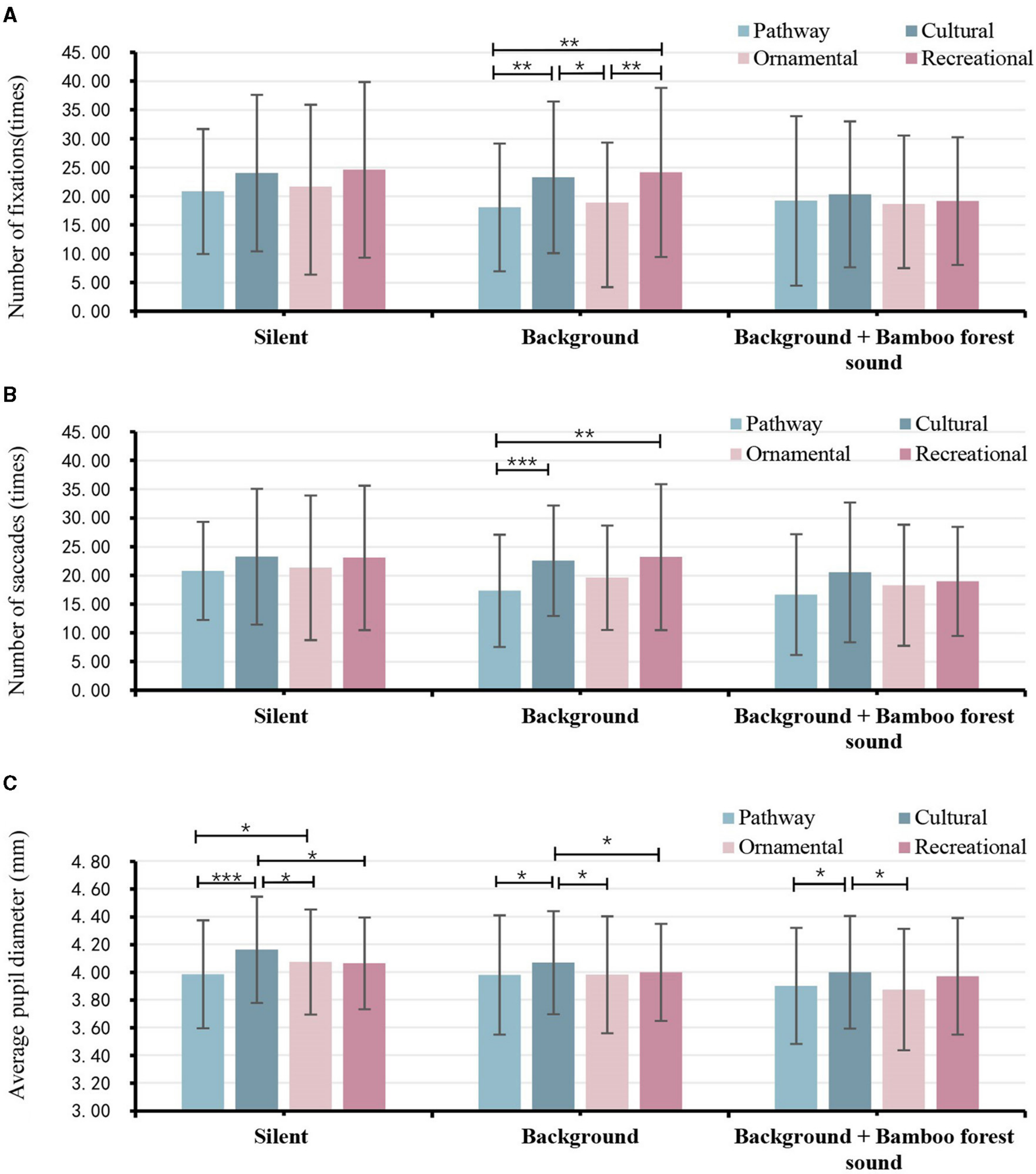

FIGURE 6
Differential comparison of eye movement metrics based on four visual spaces. **(A)** Variability in the number of fixations. **(B)** Variability in the number of saccades. **(C)** Variability in the average pupil diameter. $N = 30$; mean ± standard deviation; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; verified by repeated measures ANOVA. 1, pathway-type space; 2, cultural-type space; 3, ornamental-type space; 4, recreational-type space; a, silent sound; b, background sound; c, background sound + wind-blown bamboo sound.

4 Discussion

4.1 Effects of different visual types on eye movement indices and subjective perception

There are differences in the physiological and psychological effects of different visual types of bamboo forest space. According to previous studies, there is a significant relationship between the number of fixations and saccades indicators in eye movement behavior and the richness of the landscape images viewed by the subjects (Zhu et al., 2021). Specifically, when confronted with scenes with simple picture colors, single elements, and clear landscape structures, subjects tended to show less gaze and sweep behaviors, which reflects an unconscious visual processing mode in which fatigue can be alleviated (Zhou et al., 2023). The present study similarly confirms this view that ornamental-type and pathway-type spaces belong to the inner space of

TABLE 3 Results of repeated measures ANOVA.

Indicator	Sound type	Category III sum of squares	Df	Mean square	*F*	Statistical significance
(A) Results of repeated measures ANOVA for different visual scenes: eye-movement metrics and SRCS metrics as dependent variables, bamboo forest space as independent variable						
Number of fixations	Silent	299.625	3	99.875	1.845	0.145
	Background	842.467	3	280.822	5.740	0.001
	Wind-blown bamboo	46.067	3	15.356	0.261	0.854
Number of saccades	Silent	137.167	3	45.722	1.120	0.346
	Background	668.292	3	222.764	5.439	0.002
	Wind-blown bamboo	230.967	3	76.989	1.933	0.130
Average pupil diameter	Silent	0.473	3	0.158	6.838	0.000
	Background	0.156	3	0.052	3.342	0.023
	Wind-blown bamboo	0.308	3	0.103	4.201	0.008
Total SRCS score	Silent	92.967	3	30.989	2.836	0.043
	Background	154.625	3	51.542	4.858	0.004
	Wind-blown bamboo	69.400	3	23.133	2.459	0.068
(B) Results of repeated measures ANOVA for different auditory scenes: eye-movement metrics and SRCS metrics as dependent variables and bamboo forest space as independent variable						
Number of fixations	Pathway	116.067	1.590	72.988	0.759	0.446
	Cultural	230.289	1.648	139.704	1.763	0.187
	Ornamental	165.422	1.613	102.582	1.125	0.323
	Recreational	544.067	1.633	333.133	3.865	0.036
Number of saccades	Pathway	295.467	2	147.733	3.741	0.030
	Cultural	120.956	2	60.478	1.116	0.335
	Ornamental	138.956	1.528	90.955	1.079	0.333
	Recreational	347.489	1.641	211.764	2.951	0.072
Average pupil diameter	Pathway	0.135	2	0.067	4.784	0.012
	Cultural	0.399	2	0.200	13.359	0.000
	Ornamental	0.598	2	0.299	11.045	0.000
	Recreational	0.138	2	0.069	3.938	0.025
Total SRCS score	Pathway	216.067	2	108.033	11.339	0.000
	Cultural	227.467	1.543	147.429	9.301	0.001
	Ornamental	250.467	1.497	167.262	12.753	0.000
	Recreational	189.067	2	94.533	12.088	0.000

the jungle, with simple landscape elements, a high degree of environmental naturalness, and a high degree of integration between the bamboo forest and other environmental elements, which makes it easy to immerse oneself in the space and has a good physiological recovery effect. However, this study also found that the evaluation scores of the pathway-type space were significantly lower than those of the ornamental-type space in terms of subjective restorative evaluation indexes, which may be because the pathway-type space mainly consists of bamboo forests and roads. At the same time, the ornamental-type space also incorporates water features. Studies have shown that humans generally prefer water features, which have a unique natural charm and visual comfort and show significant advantages in environmental restorability (Luo et al., 2022). On the contrary, road elements showed lower levels of environmental preference among people, which may be related to factors such as traffic noise, dust

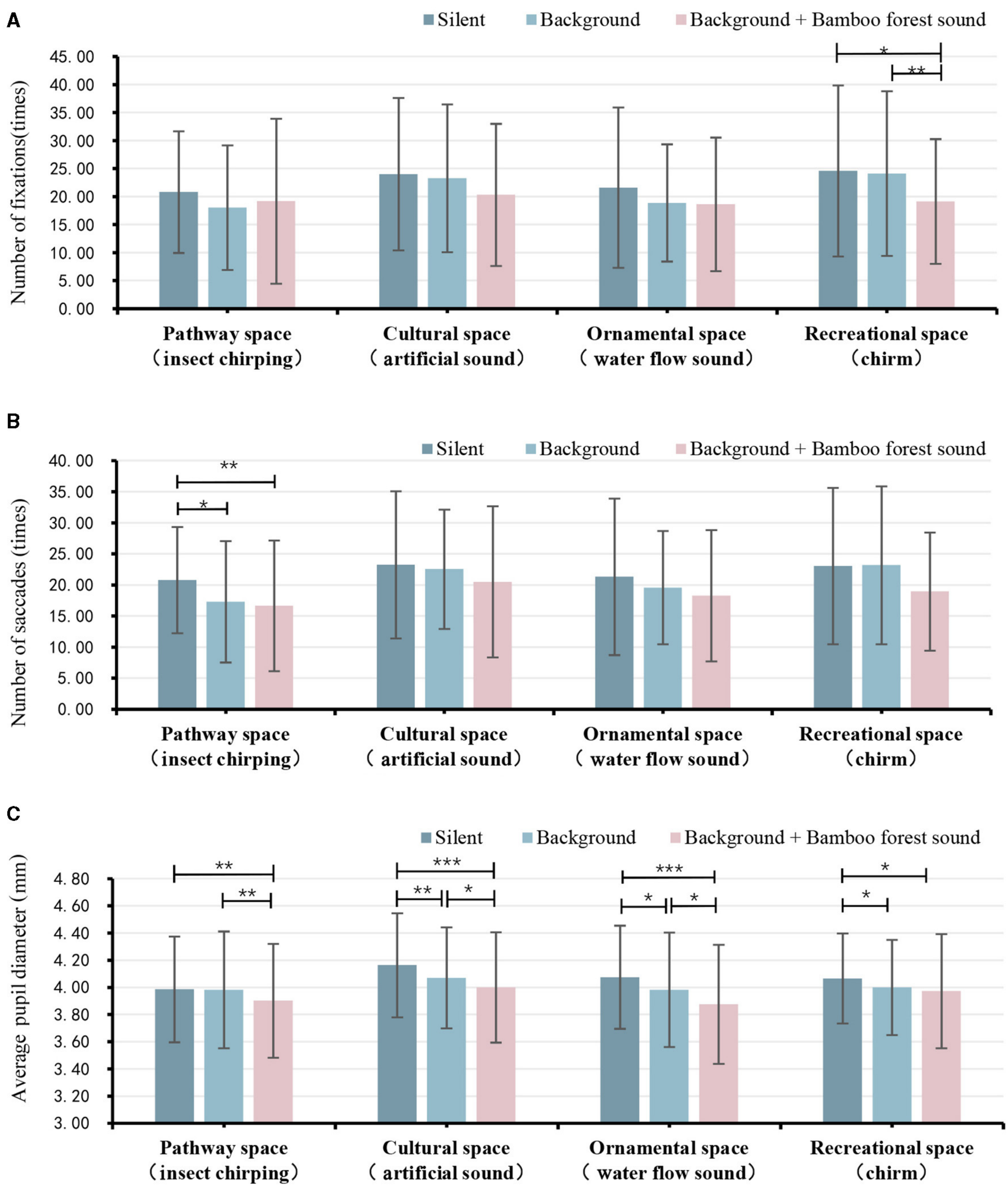

FIGURE 7
Differential comparison of eye movement metrics based on three sound conditions. **(A)** Variability in the number of fixations. **(B)** Variability in the number of saccades. **(C)** Variability in the average pupil diameter. $N = 30$; mean ± standard deviation; $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; verified by repeated measures ANOVA. 1, pathway-type space; 2, cultural-type space; 3, ornamental-type space; 4, recreational-type space; a, silent sound; b, background sound; c, background sound + wind-blown bamboo sound.

pollution, and poor overall comfort brought by roads (Hu et al., 2023).

Cultural-type and ornamental-type spaces are located at the edges of the bamboo forest space, offering a richer spatial structure compared to the other two spaces. These complex scenes often evoke curiosity and a desire to explore, which, in turn, triggers the thinking process, leading to pupil dilation and increased fixation and saccade behavior as viewers process various landscape details (Krasich et al., 2024). This heightened visual and cognitive activity consumes a significant amount of resources, potentially causing fatigue and reducing the restorative effect (Zhou et al., 2023).

However, this study also found that the average pupil diameter metrics for recreational-type spaces did not differ significantly from those of ornamental-type and pathway-type spaces. Yet, the recreational-type space received the highest subjective recovery rating among the four. This could be because the recreational-type

TABLE 4 Correlation analysis between interval-based eye movement metrics and RCS metrics.

Indicator	Totals	Being away	Fascination	Extent	Compatibility
AFD	−0.078	−0.089	−0.055	−0.043	−0.085
NoF	0.068	0.073	0.121*	0.032	0.046
ASA	−0.049	−0.025	−0.031	−0.104*	−0.021
NoC	0.046	0.059	0.094	0.023	0.013
APD	−0.040	−0.024	−0.064	0.013	−0.094

*$P < 0.05$ (two-tailed); $N = 360$.
AFD, average fixation duration; NoF, number of fixations; ASA, average saccade amplitude; NoS, number of saccades; APD, average pupil diameter.

space is more orderly and open, offering a regular landscape structure that provides a sense of stability and comfort (Ren et al., 2024). In addition, the main landscape feature in the recreational-type space is the bamboo forest lakescape. Numerous studies have confirmed that natural water elements, like lakescapes, have a positive restorative effect on physical and mental health (Jiang et al., 2023). Among the four types of bamboo forest spaces, the ornamental-type and recreational-type spaces exhibit the best restorative properties. The presence of water features significantly enhances the restorative effects of bamboo forest spaces.

4.2 Effects of different auditory types on eye movement indicators and subjective perception

Physiological and psychological effects also varied across auditory types of bamboo forest space. The study shows significant restorative effects of natural soundscapes in bamboo forests (Jeon et al., 2023), and the physiological and psychological effects of sound scenes were significantly higher than those of silent scenes in this study. For specific soundscape elements, previous studies have shown that natural soundscapes, such as chirm, insect chirping, and water flow in urban parks, can trigger positive emotions (Kogan et al., 2021; Guo et al., 2022). This study also confirms the significant physiological and psychological restorative benefits of the sounds of chirm and water flow in bamboo forest spaces. The average pupil diameter indicator of people viewing with the addition of background sound significantly decreased. The subjective restorative evaluation scores significantly increased in the recreational-type space, where the dominant sound was chirm, and the ornamental-type space, where the dominant sound was water flow, compared with the silent scene. However, this study also found that insect sounds did not show a significant restorative effect in the bamboo forest space. This phenomenon may be attributed to the fact that insect sounds in forest scenes such as bamboo forests tend to render a specific atmosphere of silence, often leading to a perceived sense of desolation and uneasiness (Soeta and Ariki, 2023). This perception may weaken the sense of shelter that restorative spaces need to have, thus failing to give people a significant restorative effect (Zhao et al., 2023).

More importantly, this study confirmed that the wind-blown bamboo sound has a high restorative benefit. According to the correlation between eye movement indicators and restorative perception and previous eye movement experiments, it is known that the average pupil diameter indicator is also related to the comfort of the landscape scene (Christopher et al., 2020). When a person is in a tense, stimulated state, the pupil dilates; when a person is in a relaxed, comfortable state, the pupil automatically contracts (Yokoi and Weiler, 2022). Compared with the silent and background sound scenes, adding wind-blown bamboo sound significantly decreased the number of fixations and average pupil diameter indicators. It significantly increased the subjective restorative evaluation scores for the four types of spaces, which shows that bamboo forest sound has a very high restorative value. In addition, this study also found that soundscape has a guiding effect on human visual attention. Comparing the changes in eye movement heat maps under the three auditory types in the same space, it can be seen that the sound of insect chirping can increase the subjects' attention to the road area, the sound of artificial sound can increase the subjects' attention to the area of the manmade building, the sound of running water can focus the subjects' attention significantly at the water flow, the sound of chirm can increase the subjects' attention to the elements of the plants and the sky, and the sound of wind-blown bamboo can increase the subjects' attention to the elements of the plants of the bamboo forest.

4.3 Design strategies for future audiovisual restorative environments in bamboo forest spaces

As a good recreational environment, bamboo forest space can be physiologically and psychologically linked to human perception (Lu et al., 2020). This study confirms through eye movement experiments and subjective restorative factor scales that different types of bamboo forest spaces can have different effects on human physiology and psychology and that the visual creation modes of recreational-type and ornamental-type spaces, as well as the three types of soundscapes, namely, bamboo sound, water flow, and chirm, can shape a good restorative experience for bamboo forest spaces. People's subjective and objective responses to each audiovisual scene can provide a more effective reference basis for the optimization and enhancement of the bamboo forest space, as well as the construction of restorative environments (Park et al., 2019). In the visual scene creation, it can appropriately enrich the sense of color of the bamboo forest space, use herbs and small shrubs to increase the plant level, use the lake view, streams, and other water features to create a certain degree of visual openness, and appropriately reduce the density of the bamboo forest, so as to enhance the people's interest in the space and the sense of exploration, but at the same time, we should also pay attention to ensure that the scene of the overall integration of the scene, to avoid the elements of too much lead to visual fatigue. Regarding soundscape creation, the space design should focus on guiding and strengthening the natural soundscape and provide people with facilities and environments where they can stop and listen (Zhu et al., 2024). On the one hand, the sound of water flow, wind-blown bamboo, and chirm can be emphasized by guiding the wind direction and creating water features through plant planting, spatial terrain differences, and shaping of mountains and stone elements. On the other hand, plants with broad and thick leaves, such as plantains, lotus families, and other types of plants, can be planted in the static lake area to create a unique soundscape of rainwater dripping down (Yang and Kang, 2022) or the natural soundscape can be played in the bamboo forest by artificial means using instruments, and listening pavilions, corridors, and rest seats can be installed for tourists to stop by, shaping the area of the punch card specializing in listening to the soundscape.

4.4 Limitations

There are some limitations in this study that should be considered. First, the audiovisual elements of bamboo forest space can be further subdivided, and this experiment mainly explored the four types of bamboo forest space and the corresponding background sound and wind-blown bamboo sound. The audiovisual elements have some limitations, and in the future, the montage method can be used to add a combination of different audiovisual elements in the original pure bamboo forest scene to assess the impact of specific elements on the restorative environment of bamboo forest space in a more detailed way. Second, only college students were selected as the research population for this experiment, and there are limitations in the scope of application of the study. In the future, we can consider recruiting people from different geographical environments, different age groups, and different education levels to conduct extensive research to make the conclusions of the study more generalizable.

5 Conclusion

In this study, the physiological and psychological effects of people in different bamboo forest audiovisual scenarios were investigated using eye movement analysis techniques, focusing primarily on audiovisual perception. The study explored the audiovisual characteristics that affect the restorative effects of bamboo forest space. The results indicate that bamboo forest spaces with varying audiovisual features provide different degrees of restorative benefits.

In terms of visual characteristics, the best restorative effects were found in recreational-type bamboo spaces and ornamental-type bamboo spaces. Auditory features, such as the sound of wind-blown bamboo, flowing water, and birds chirping, significantly enhanced the subjective restorative perception of bamboo forest spaces. These sounds also reduced the number of fixations and the average pupil diameter.

Moreover, this study found that soundscape guides people's visual attention, with bamboo forest sounds increasing focus on natural elements. In addition, there is a significant connection between the restoration potential of bamboo forest spaces and eye movement indicators. Ductility is significantly positively correlated with the number of fixations indicator, while fascination is significantly negatively correlated with the average saccade amplitude indicator.

Based on these findings, optimization strategies can be proposed for creating restorative environments in bamboo forest space based on people's subjective and objective responses to the audiovisual elements of bamboo forest space. Visually, the attractiveness of the bamboo forest space can be enhanced by creating water features and enriching the color levels of the space. Audibly, the natural soundscape can be strengthened through natural guidance and artificial creation to create a comfortable place atmosphere.

This study deepens our understanding of the impact of bamboo forest spaces on human health and provides a reference for future design strategies to create restorative environments in bamboo forest spaces.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Sichuan Agricultural University Human Ethical and Welfare Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

CZ: Conceptualization, Formal analysis, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. XF: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. JL: Writing – original draft. SF: Investigation, Writing – review & editing. TL: Writing – review & editing. WW: Writing – review & editing. XL: Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1415514/full#supplementary-material

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