

Article

An Experimental Study on the Effects of Natural Visual and Auditory Stimuli on Human Physiological and Psychological Responses Under Different Temperature Conditions

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Abstract

Although many studies have demonstrated the positive effects of natural visual and auditory stimuli on human physiological and psychological states, there is limited empirical evidence on the effects on subjective comfort under different thermal environments. This study used a climatic chamber experiment to evaluate the impact of three types of natural stimuli (visual, auditory, and combined audio-visual) on physiological and psychological responses under three operative temperature conditions (26 °C, 28 °C, and 32 °C). In total, 24 participants were recruited. Physiological indicators, including heart rate variability, skin conductance level (SCL), skin temperature (ST), and blood pressure, as well as psychological indicators including thermal sensation (TSV), thermal comfort (TCV), visual comfort (VCV), and acoustic comfort (ACV), were collected. The results show that TCV was significantly and positively correlated with both VCV and ACV. The visual stimuli produced the most significant decrease in TSV and the greatest increase in TCV, while combined audio-visual stimuli had the most significant impact on physiological responses. At 26 °C, the combined audio-visual stimuli group reduced heart rate by 6.08%. However, at 32 °C, most physiological and psychological restoration indicators showed no significant changes. These findings provide theoretical references for health-oriented multisensory environmental design in urban areas.

Keywords: thermal environment; multisensory interaction; audio-visual stimuli; physiological parameters; thermal comfort

1. Introduction

With the rapid acceleration of urbanization [1,2], human daily activities have become increasingly concentrated within indoor environments. Studies show that humans spend approximately 90% of their time indoors [3], making Indoor Environmental Quality (IEQ) a significant determinant of human health, psychological state, and behavioral performance [4,5]. IEQ consists of thermal, acoustic, and luminous environments, as well as air quality [6,7]. Among these, the thermal environment directly influences physiological responses and comfort [8], while the acoustic and luminous environments affect human physiological and psychological states through auditory and visual stimuli [9]. Notably, recent studies have further shown that the luminous environment affects not only visual comfort, but also that illuminance level, spectral composition, and correlated colour temperature (CCT) may jointly influence thermal sensation, thermal comfort evaluation, and



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subjective judgments of air quality [10–12]. Meanwhile, in recent years, the concept of Biophilic Design has gained prominence, emphasizing the integration of natural auditory and visual elements to strengthen the emotional and physiological connection between humans and nature. The goal is to enhance occupants' physical and mental health and overall well-being [13–16]. However, research on the effects of natural auditory and visual stimuli on human physiological and psychological recovery under different thermal conditions remains limited. Therefore, it is of both theoretical and practical significance to investigate the comprehensive effects of auditory and visual stimuli on humans across different temperature conditions. Such research can provide essential theoretical support for optimizing architectural environments.

1.1. Effects of Auditory and Visual Stimuli on Human Physiology and Psychology

Auditory and visual stimuli, as critical components of multisensory environmental research, significantly influence human physiological and psychological states. Numerous studies have demonstrated that exposure to natural visual stimuli, such as greenery, offers restorative experiences, reduces stress, improves mood, and enhances cognitive function [17–19]. Lee et al. found that a view of a green rooftop for just 40 s significantly improved participants' attention span [20]. Ulrich et al. found in an earlier study that patients exposed to natural views resulted in faster postoperative recovery (shorter hospital stays) and reduced pain complaints, highlighting the health-promoting effects of visual exposure to nature [21]. Elsadek et al. investigated the effects of 90 m high-rise window views on well-being through measurements of brain activity, and the findings indicated that green space with water outside the window or green space alone produced the most beneficial results [22]. Donggeun et al. employing virtual reality technology, demonstrated that increasing the proportion of urban environments in visual stimuli leads to heightened psychological and physiological stress responses among building occupants [23]. Chen et al. found that outdoor window views help participants maintain better health during exercise. Specifically, the incidence of dizziness decreased by 10.42% and 8.28%, and the level of fatigue was reduced by 4.04% and 2.52% during moderate- and high-intensity exercise, respectively [24]. Auditory stimuli also play a vital role in physiological and psychological recovery. Studies have shown a general preference for natural sounds, such as birdsong and flowing water [25,26]. Pellegatti et al. investigated the effects of different sound types in naturally ventilated environments on students. The results show that natural sounds produced by opening windows consistently had a positive impact on students' learning performance and comfort [27]. Similarly, Jo further demonstrated that exposure to forest sounds significantly reduced prefrontal oxyhemoglobin concentration, sympathetic activity, and heart rate, while enhancing subjective comfort and mood states [28]. Xie et al. compared the effects of environmental noise exposure and natural sound intervention on patients' perceptions, physiological, and psychological outcomes. The results show that exposure to natural sounds improved patients' auditory perception and reduced pain. Moreover, natural sounds effectively alleviated physiological and psychological stress, while also reducing physiological fluctuations during surgical procedures [29]. Sun et al. investigated the effects of the acoustic environment in enclosed offices on cognitive performance and relaxation states. The study found that participants exposed to classical music as background sound reported higher levels of emotional pleasure and a greater sense of dominance compared to other conditions [30].

The combination of visual and auditory stimuli generates a compound effect of multisensory stimulation. Numerous studies have shown that the synergistic effect of visual and auditory inputs can produce more pronounced physiological and psychological restorative effects than unimodal stimuli alone [31,32]. Liu et al. conducted an eye-tracking

experiment and found that the combination of forest landscapes with birdsong, insect sounds, flowing water, or light music and temple bells significantly enhanced participants' sense of immersion and engagement, while effectively reducing psychological stress [33]. Similarly, Li et al. compared the effects of different presentation modalities (video-sound, image-sound, sound-only, and video-only) on physiological and psychological responses, and their results indicated that combining static images with natural sounds could significantly enhance physiological comfort and subjective restoration [34]. Furthermore, Li and Liu demonstrated that the combination of green landscapes with natural sounds such as birdsong and water could enhance restorative outcomes via emotional and preference pathways. Additionally, specific types of natural sounds (e.g., birdsong) were found to have a positive regulatory effect on certain landscape elements (e.g., waterscapes), thereby promoting emotional well-being [35].

In summary, existing research provides ample evidence for the synergistic benefits of natural visual and auditory stimuli on human physiological and psychological health. However, most current studies focus primarily on stress relief and emotional improvement. There remains a relative lack of attention to psychological responses related to environmental adaptation, such as indoor environmental perception and comfort evaluation. Future research should therefore expand in this direction.

1.2. Impact of Temperature on Audio-Visual Perception and Comfort

Among the components of IEQ, the thermal environment is one of the indoor environmental factors that received systematic attention relatively early and has remained a major focus of research [6,8,36]. Human thermal sensation is jointly determined by six major factors: metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and humidity [36]. Accordingly, international standards generally recommend operative temperature as an important indicator for thermal environment evaluation [36,37]. This parameter takes into account the combined influence of air temperature and mean radiant temperature on convective and radiative heat exchange in the human body, and therefore reflects actual human heat exchange conditions more comprehensively than indoor air temperature alone.

In addition to auditory and visual stimulation, the interaction between the luminous environment and thermal perception has received increasing attention in recent years. Bellia et al. recruited 163 volunteers to investigate the interaction between light color and the thermal environment in a controlled laboratory. Two lighting scenarios were set (warm light: 3000 K; cool light: 6000 K), with work plane illuminance maintained at 300 lx, while operative temperature was set at 20 °C and 25 °C. The results show that warm light induced a warmer thermal impression [38]. Toftum et al. found that correlated colour temperature influences not only visual perception, but also occupants' perceptions of other indoor environmental factors, such as the thermal environment and air quality [10]. Furthermore, Chinazzo et al. combined three daylight illuminance levels (low: approximately 130 lx; medium: approximately 600 lx; high: approximately 1400 lx) with three operative temperature conditions (19 °C, 23 °C, and 27 °C), and assessed both subjective thermal responses and physiological parameters in 84 participants. The results indicate that, under cold conditions, low daylight illuminance reduced thermal comfort, whereas under warm conditions, low daylight illuminance actually helped improve thermal comfort [39].

Previous studies have also shown that excessively high or low air temperatures may have adverse effects on health [40,41]. In addition, temperature not only significantly influences individuals' perceptions of other environmental factors, but may also itself be modulated by them. In a controlled experimental study conducted within an open-plan office environment in a North American Mediterranean climate zone, Mirmadi et al.

systematically varied temperature, lighting correlated colour temperature, and noise as primary independent variables, while continuously monitoring and regulating indoor environmental parameters including air temperature, relative humidity, and CO₂ concentration. The results demonstrate that temperature significantly modulated the effects of both the acoustic and luminous environments on selective attention and subjective comfort, with acoustic comfort exhibiting statistically significant variation across different temperature conditions [42]. Ko et al. conducted a randomized crossover experiment with 86 participants in a controlled laboratory setting. Under a slightly warm operative temperature of 28 °C, CO₂ levels were monitored and clothing conditions were standardized. The results show that window views enhanced participants' tolerance of the slightly warm thermal environment, promoted positive emotions, and reduced negative emotions [43]. Du et al. investigated the influence of natural window views on thermal sensation under different indoor temperatures in controlled laboratory settings. With operative temperatures set at 23 °C, 26 °C, and 28 °C and illuminance levels at 150 lx, 300 lx, and 500 lx, the results show that the presence of natural window views significantly shifted participants' thermal sensation toward neutrality, especially under slightly warm conditions (28 °C) [44]. Jiang et al. further investigated the effects of natural window views and daylight on thermal perception under different thermal conditions, finding that they enhanced participants' thermal comfort and health perceptions in cooler environments. The study was conducted in a controlled laboratory setting, with three operative temperature conditions (17 °C, 20 °C, and 23 °C) arranged in spaces with and without windows, to compare the short-term effects of natural view and daylight exposure on thermal perception, physiological indicators, and health-related perceptions [45]. Gu et al. provided visual stimulation through artificial windows at temperatures of 22 °C, 25 °C, and 28 °C. The results show that artificial windows effectively weakened participants' perception of uncomfortable temperatures in underground spaces and improved thermal acceptability [46]. Geng et al. conducted experiments in a controlled office environment while simultaneously measuring air temperature, relative humidity, CO₂ concentration, illuminance, and background noise. Their results show that changes in the thermal environment not only affect thermal comfort, but also further influence occupants' perceptions of other Indoor Environmental Quality factors [47]. In addition, Ibrahim et al. demonstrated that, in building shading design, multi-objective optimization can be used to balance daylighting performance, visual comfort, and energy performance simultaneously, indicating that indoor environmental design is gradually shifting from single-dimensional optimization to multi-dimensional integrated optimization [48].

In summary, current research on the restorative effects of visual and auditory stimuli mainly focuses on thermoneutral or slightly cool comfort zones. However, there is a lack of systematic studies on how different temperature conditions within neutral to moderately warm ranges affect the restorative effects of visual, auditory, and combined stimuli, which merits further investigation.

1.3. Study Aims

Although numerous studies have demonstrated that natural visual and auditory stimuli in neutral or comfortable environments can promote individuals' physical and psychological recovery, such as relieving stress and improving emotional states, current research still has two key limitations. First, the restorative effects of natural visual and auditory stimuli in warm or elevated temperature environments have been insufficiently investigated. Second, existing studies have primarily focused on psychological responses such as stress relief and emotion regulation, while relatively little attention has been paid to

how visual and auditory stimuli influence individuals' subjective environmental perception and multidimensional comfort evaluations under varying temperature conditions.

Therefore, this study takes natural visual, auditory, and combined audio-visual stimuli as the entry point, conducting experiments across different thermal environments to elucidate the restorative effects of natural visual and auditory stimuli under varying thermal conditions. The specific aims of this study are as follows:

- (1) To systematically investigate the effects of natural visual, auditory, and combined stimuli on individuals' physiological and psychological recovery;
- (2) To examine the influence of temperature on the restorative effects of natural visual and auditory stimuli;
- (3) To analyze the correlations among subjective perceptual indicators such as thermal sensation, thermal comfort, visual comfort, and acoustic comfort.

By systematically investigating the restorative effects of different types of natural visual and auditory stimuli under various thermal conditions, this study aims to expand the scope of restorative environment research and provide a theoretical foundation for the development of health-oriented built environments.

2. Methods

2.1. Experimental Environment

This experiment was conducted from July to August 2024 in a controlled laboratory at Hunan University (Changsha, China, 28.2° N, 112.9° E). Changsha is located in the hot-summer and cold-winter region of China and has a subtropical monsoon climate with hot and humid summers. To realistically simulate the typical thermal and humid environment of local buildings in summer, three operative temperature conditions were established: 26 °C, 28 °C, and 32 °C. The 26 °C setting corresponds to the minimum summer air-conditioning setpoint recommended by the Chinese government [49]. The 28 °C condition corresponds to the typical indoor temperature of naturally ventilated buildings in summer [50], while 32 °C reflects the typical indoor temperature of non-air-conditioned rooms in Changsha during summer [51]. For all temperature settings, the relative humidity was consistently maintained at 60% to 70%, which reflects the typical indoor humidity range commonly observed in Changsha, Hunan Province [51], thereby realistically simulating the local hot-humid summer environment. All participants signed informed consent forms, and the experimental procedures strictly adhered to ethical guidelines.

As shown in Figure 1a, the chamber measures 2.2 m × 3.6 m × 3 m (length × width × height). The walls are constructed from high-performance thermal insulation polystyrene foam composite steel plates, finished with white opaque wallpaper. The south wall features an artificial window. The south-facing wall features an artificial window, implemented using a 1440 mm × 810 mm 4K ultra-high-definition monitor (65Z770MF, Toshiba, Qingdao, China). This monitor can be covered with a white panel to simulate a windowless condition or left uncovered to simulate a windowed condition. This type of monitor-based artificial window has been validated in previous studies as an effective method for visual simulation [52,53]. The experimental design included a control group (C), which involved an environment without a window view or sound. The experimental visual stimuli only group (W) presented a typical green landscape from the library at Hunan University, characterized by an open view and abundant vegetation. Previous studies have shown that such environments are more likely to elicit positive preferences among participants [54]. To quantify the visual characteristics of the selected scene, the Green View Index (GVI) was calculated using Python 3.9 image processing techniques, yielding a value of 80% (W-GVI = 80%). Details of the visual stimuli are shown in Figure 1b.

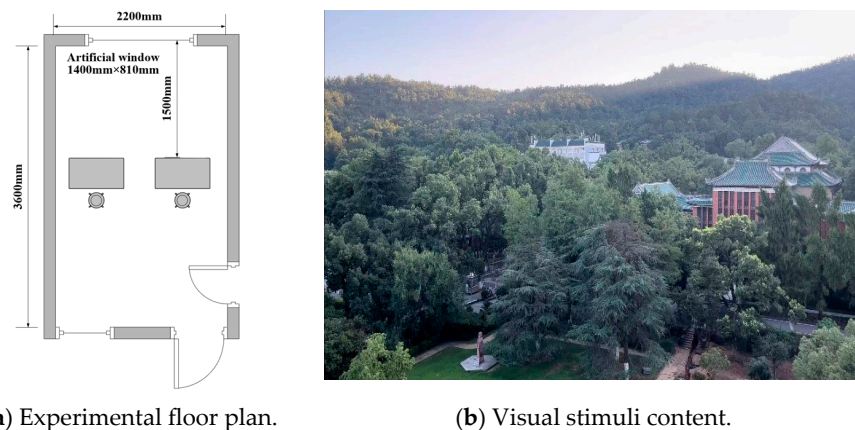


Figure 1. Window view video content and experimental floor plan.

To further investigate the effect of auditory stimuli on the psychological and physiological state of individuals, this experiment established an auditory stimuli only group (S), with birdsong used as the auditory stimuli. Birdsong is widely recognized as a restorative sound; prior research indicates that it can enhance environmental pleasantness and resilience, alleviate stress, and improve mood [55]. The stimuli were delivered through the monitor's built-in speakers at 45 dB(A), a level shown to approximate gentle natural listening conditions while providing favorable acoustics for participants [56].

In addition, a combined audio-visual stimuli group (W + S) was established to evaluate the joint effects of green landscapes and natural sounds on participants' physiological restoration and environmental perception. The specific experimental conditions are detailed in Table 1.

Table 1. Experimental conditions.

Temperature	Group	Audio-Visual Stimuli Conditions
26 °C/28 °C/32 °C	C	control group without window view or sound
	S	auditory stimuli only
	W	visual stimuli only
	W + S	combined audio-visual stimuli

2.2. Participants

Prior to the experiment, a statistical power analysis was conducted to determine the minimum required sample size [57]. Assuming an effect size of 0.25, $\alpha = 0.05$, and power $(1 - \beta) = 0.8$, the minimum sample size was calculated to be 24 participants using G*Power 3.1 software. A total of 24 participants (12 males and 12 females) were recruited for this experiment. All participants had lived in Changsha for at least one year. The height, weight and current physical condition of the participants were collected through a questionnaire. All participants were in good health, with no history of serious illnesses such as heart disease, asthma or hypertension, and did not take any medication during the experiment. The participants' personal information is presented in Table 2.

To ensure experimental control, participants were instructed to refrain from smoking, drinking alcohol, consuming caffeinated beverages, or engaging in strenuous exercise within 24 h prior to the experiment. During the experiment, all participants wore standardized short-sleeved T-shirts and long pants. According to the ASHRAE-55 standard, the thermal resistance of the clothing was 0.5 clo [36].

Table 2. Detailed information on participants.

	Sample Size	Age	Height (cm)	Weight (kg)	BMI ^a (kg/cm ³)
Male	12	22.25 ± 2.38 ^b	175.75 ± 5.91	72.29 ± 15.38	23.35 ± 4.35
Female	12	20.92 ± 2.64	163.75 ± 6.34	56.41 ± 3.81	21.09 ± 1.92
All	24	21.58 ± 2.55	169.75 ± 8.57	64.35 ± 13.63	22.22 ± 3.48

^a Body Mass Index (BMI) = Mass (kg)/Height (m)². ^b Standard deviation.

2.3. Measurements

2.3.1. Environmental Parameter Measurements

Throughout the experiments, various environmental parameters were continuously monitored. The monitored parameters included indoor air temperature (T_a), relative humidity (RH), black globe temperature (T_g), carbon dioxide concentration (CO_2), and air velocity (v_a), all measured at a height of 0.6 m above the floor, corresponding to the standard instrument position for seated participants [36]. These parameters were automatically recorded at one-minute intervals using data acquisition devices, with details of the measurement instruments provided in Table 3. In addition, desktop illuminance and correlated color temperature in the workstation area, as well as sound pressure level.

Table 3. Measurement parameters and experimental instruments.

Instrument	Parameter	Measuring Range	Accuracy
MX1102 (Onset Computer Corporation, Bourne, MA, USA)	Air temperature	0–50 °C	±0.21 °C
	Relative humidity	1–90%	±2%
	CO ₂	0–5000 ppm	±50 ppm
HD32.3 (Delta OHM, Caselle di Selvazzano, Italy)	Air temperature	−40–100 °C	±0.1 °C
	Black globe temperature	−30–120 °C	±0.1 °C
	Relative humidity	15–90%	±2%
HPCS320D (Hopocolor, Hangzhou, China)	Air velocity	0–5 m/s	±0.05 m/s
	Illumination	5–200,000 lx	±4%
	Color temperature	1000–100,000 K	±50 K
AR814 (Smart Sensor, Dongguan, China)	Sound pressure level	30~130 dB	±1.5 dB
PC-80B (Creative Medical, Shenzhen, China)	Heart rate variability	30 bpm–240 bpm	±2 bpm
DS1922L (Analog Devices, San Jose, CA, USA)	Skin temperature	−45 °C–85 °C	± 0.5 °C
KD-5907 (Andon Health, Tianjin, China)	Blood pressure	0–300 mmHg	±3 mm Hg
Galvanic Skin Response Sensor (Sizhirui Technology, Zhengzhou, China)	Skin conductance	-	0.1 µS

The results of the measured environmental parameters are presented in Table 4. During the experiment, the average indoor air velocity was consistently below 0.1 m/s, and the carbon dioxide concentration remained within the standard range, ensuring that these factors did not adversely affect the experimental results. The lighting condition was maintained at a correlated color temperature of approximately 5200 K and a desktop illuminance of approximately 400 lx across all experimental sessions. According to GB 50034-2024 [58], the illuminance standard value for ordinary offices is 300 lx, and the intermediate color range for office applications spans 3300 K to 5300 K. The settings adopted in this study fall within these ranges and are representative of typical office lighting environments in China. Based on the measured air temperature, globe temperature, and

air velocity, the mean radiant temperature (T_r) and operative temperature (T_{op}). Mean radiant temperature was derived from the black globe temperature using the following equation [59,60]:

$$T_r = [(T_g + 273)^4 + \frac{1.1 \times 10^8 \cdot v_a^{0.6}}{\varepsilon_g \cdot D^{0.4}} (T_g - T_a)]^{1/4} - 273 \quad (1)$$

where $\varepsilon_g = 0.95$ is the emissivity of the globe thermometer, $D = 0.05$ m is the globe diameter, and v_a is the air velocity measured simultaneously. Since the average indoor air velocity during all experimental sessions was consistently below 0.1 m/s and participants were engaged in sedentary activity without direct solar exposure, operative temperature was then calculated as the arithmetic mean of air temperature and mean radiant temperature [36]:

$$T_{op} = \frac{T_a + T_r}{2} \quad (2)$$

Table 4. Measured environmental parameters in the experimental setting.

Parameter	26 °C Condition	28 °C Condition	32 °C Condition
T_a (°C)	26.2 ± 0.2	27.8 ± 0.1	32.2 ± 0.4
T_g (°C)	26.1 ± 0.2	27.6 ± 0.1	32.0 ± 0.4
v_a (m/s)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
T_r (°C)	26.1 ± 0.2	27.6 ± 0.1	32.0 ± 0.4
T_{op} (°C)	26.2 ± 0.2	27.7 ± 0.1	32.1 ± 0.4
RH (%)	64.8 ± 3.2	70.0 ± 2.7	68.6 ± 2.5
CO ₂ (ppm)	570.5 ± 97.2	564.3 ± 110.3	580.3 ± 103.6
Desktop illuminance (lx)	404 ± 3	397 ± 7	401 ± 2
Color temperature (K)	5202 ± 30	5179 ± 48	5178 ± 71
Sound pressure level (dB)	44.8 ± 0.5	45.2 ± 0.6	45.2 ± 0.4

Statistical analysis indicated that, except for operative temperature, there were no significant differences in the other environmental parameters under different experimental conditions.

2.3.2. Physiological Measurements

In this study, the physiological parameters collected were heart rate variability (HRV), skin conductance level (SCL), mean skin temperature (ST), and blood pressure. Details of the measurement instruments are provided in Table 3. HRV analysis encompassed both time-domain and frequency-domain indices. In this study, we focused primarily on time-domain metrics, including the standard deviation of normal RR intervals (SDNN), the root mean square of successive differences between adjacent RR intervals (RMSSD), and the percentage of adjacent RR intervals differing by more than 50 ms (pNN50).

All of these physiological indicators are closely related to autonomic nervous system (ANS) activity and can reflect individuals' stress responses and emotional regulation in response to external stimuli [61]. The ANS comprises the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS), which are responsible for arousal and recovery processes, respectively. Visual and auditory stimuli can modulate the ANS, resulting in changes in these physiological indicators. When SNS activity decreases or PNS activity increases, heart rate (HR) typically decreases. SDNN, RMSSD, and pNN50 are recognized indicators of PNS activity; higher values generally indicate a relaxed and restorative state, reflecting lower levels of physiological stress [62]. SCL reflects sweat gland activity, which is regulated by the SNS, and is commonly used as a psychophysiological

index to assess stress, as increased stress leads to elevated SCL [63]. In this study, SCL was measured using a skin conductance sensor, with electrodes attached to two fingers on the participant's left hand. ST is also closely associated with SNS activity; SNS activation induces peripheral vasoconstriction, thereby reducing skin temperature [64]. According to previous studies, the five-point method was used to measure ST in this experiment [65], with measurement sites including the cheek, upper arm, abdomen, back, and thigh. The mean skin temperature was calculated as the following equation:

$$ST = 0.07 T_{\text{cheek}} + 0.19 T_{\text{arm}} + 0.175 T_{\text{abdomen}} + 0.175 T_{\text{back}} + 0.39 T_{\text{thigh}} \quad (3)$$

In addition, an electronic sphygmomanometer was used to record systolic blood pressure (SBP) and diastolic blood pressure (DBP) during the experiment. It is important to note that negative emotions, such as tension and anxiety, may cause an increase in participants' blood pressure during the experimental procedures.

2.4. Subjective Questionnaires

In this study, subjective questionnaires were used to collect participants' thermal sensation vote (TSV), thermal comfort vote (TCV), acoustic comfort vote (ACV), and visual comfort vote (VCV). The TSV was assessed using a 9-point continuous scale [66], which is an extension of the ASHRAE 7-point scale, ranging from cold (−3) to hot (+3), with the following specific points: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2), and hot (+3). To more accurately evaluate comfort, the TCV, ACV, and VCV were evaluated using a 6-point scale [67], with endpoints of very uncomfortable (−2) and very comfortable (+2), and intermediate breakpoints of slightly uncomfortable (−0.01) and slightly comfortable (+0.01). Detailed descriptions of these scales are shown in Figure 2.

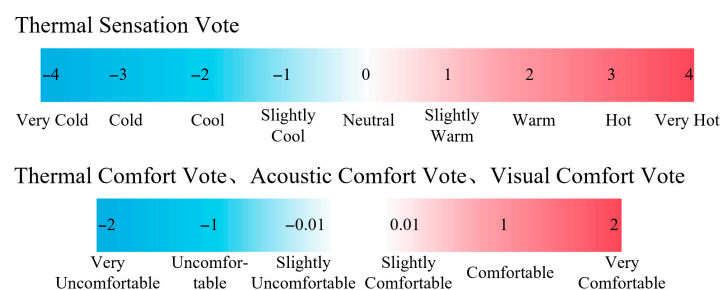


Figure 2. Subjective questionnaire scales used in the experiment.

2.5. Experimental Procedure

A within-subjects crossover experimental design was adopted in this study to ensure that each participant experienced all temperature conditions (26 °C, 28 °C, and 32 °C) as well as different combinations of sensory stimuli: auditory stimuli only (S), visual stimuli only (W), and combined audio-visual stimuli (W + S). The experimental procedure is illustrated in Figure 3. In order to reduce the order and learning effects, this study employed a Latin square design to counterbalance the temperature conditions. However, within each temperature condition, the sensory exposure sequence after the control group (C) was kept fixed as S, W, and W + S. To avoid interference between stimulus phases, a 5 min neutral environmental recovery period was set between each stimulus phase [68]. During this period, participants sat with their eyes closed to eliminate any visual residual effects. In addition, to minimize carryover effects from previous sessions, each participant was scheduled with an interval of more than 24 h between experimental sessions.

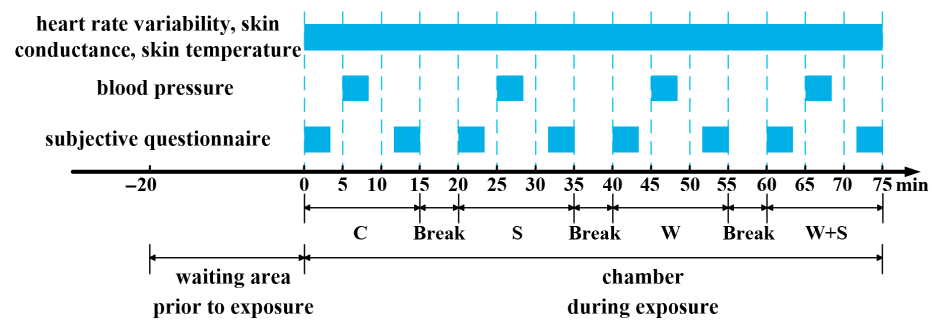


Figure 3. Experimental process.

The air-conditioning system, as well as all environmental monitoring instruments, was activated two hours before the experiment to ensure that the indoor environmental parameters met the design specifications and remained stable. During the experiment, to avoid potential interference from the participants' prior thermal experiences, they were required to arrive at the laboratory 20 min in advance and acclimate in a neutral environment at 26 °C. After acclimatization, participants wore electrocardiogram monitors, skin conductance sensors, and skin temperature sensors, then entered the experimental chamber. The environmental temperature was kept constant throughout each experimental session. At the start of the experiment, participants first sat quietly for 15 min in the no-window view, no-sound condition (C), completed the initial subjective questionnaire, and performed a second questionnaire and blood pressure measurement before the 15 min period ended, serving as baseline measurements. Participants then sequentially experienced auditory stimuli only (S, 15 min), visual stimuli only (W, 15 min), and combined audio-visual stimuli (W + S, 15 min). After each stimulus phase, participants completed two subjective questionnaires and one blood pressure measurement. Throughout the experiment, participants were instructed to focus on the presented visual and auditory stimuli while remaining still, awake, and alert.

2.6. Statistical Analyses

Data analysis was performed using IBM SPSS 27 and Origin 2024 software. Before the analysis, outliers were removed using the boxplot outlier detection method. The Kolmogorov–Smirnov test was then conducted to assess whether the data followed a normal distribution, followed by correlation analysis. If the data followed a normal distribution, paired *t*-tests were used to compare differences between the experimental groups (W, S, W + S) and the no-window view, no-sound control group (C); if the data did not follow a normal distribution, the Wilcoxon paired sample test was applied. To control for false positives, the Bonferroni correction was used to adjust the critical alpha level for each hypothesis. The *p* values reported in Section 3 are Bonferroni-adjusted *p* values generated by IBM SPSS 27. Accordingly, the significance annotations in the figures have been revised to reflect these adjusted values. In all analyses, * indicates significance at the adjusted 0.05 level (Bonferroni-corrected $p < 0.05$), and ** indicates significance at the adjusted 0.001 level (Bonferroni-corrected $p < 0.001$). To assess the effect size of visual and auditory stimuli, Cohen's *d* value was used, with effect sizes classified as negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (>0.8).

3. Results

This section presents the experimental outcomes of participants' physiological and psychological indicators under different operative temperature conditions with visual, auditory, and combined audio-visual natural stimuli. Physiological outcomes include heart rate variability, skin conductance level, skin temperature, and blood pressure. Psychological

outcomes include thermal sensation, thermal comfort, visual comfort, and acoustic comfort. All data was compared to a control group. This helped show clear differences between each stimulus condition.

3.1. Physiological Response

3.1.1. Heart Rate Variability

Figure 4a shows the changes in heart rate (HR) under different visual and auditory stimuli conditions at different operative temperatures. At 26 °C, compared to the control group C (77.96 ± 11.87 bpm), all three stimulus conditions significantly reduced the average HR (S: 77.01 ± 10.88 bpm, $p = 0.01$; W: 74.93 ± 12.30 bpm, $p < 0.001$; W + S: 73.22 ± 10.32 bpm, $p = 0.001$), with the W + S group showing the greatest reduction. At 28 °C, HR in the control group increased to 80.11 ± 10.18 bpm, but the W (78.72 ± 10.40 bpm, $p = 0.022$) and W + S (75.33 ± 9.28 bpm, $p < 0.001$) groups still effectively suppressed the increase in HR. At 32 °C, no significant differences in HR were observed between the groups ($p > 0.05$).

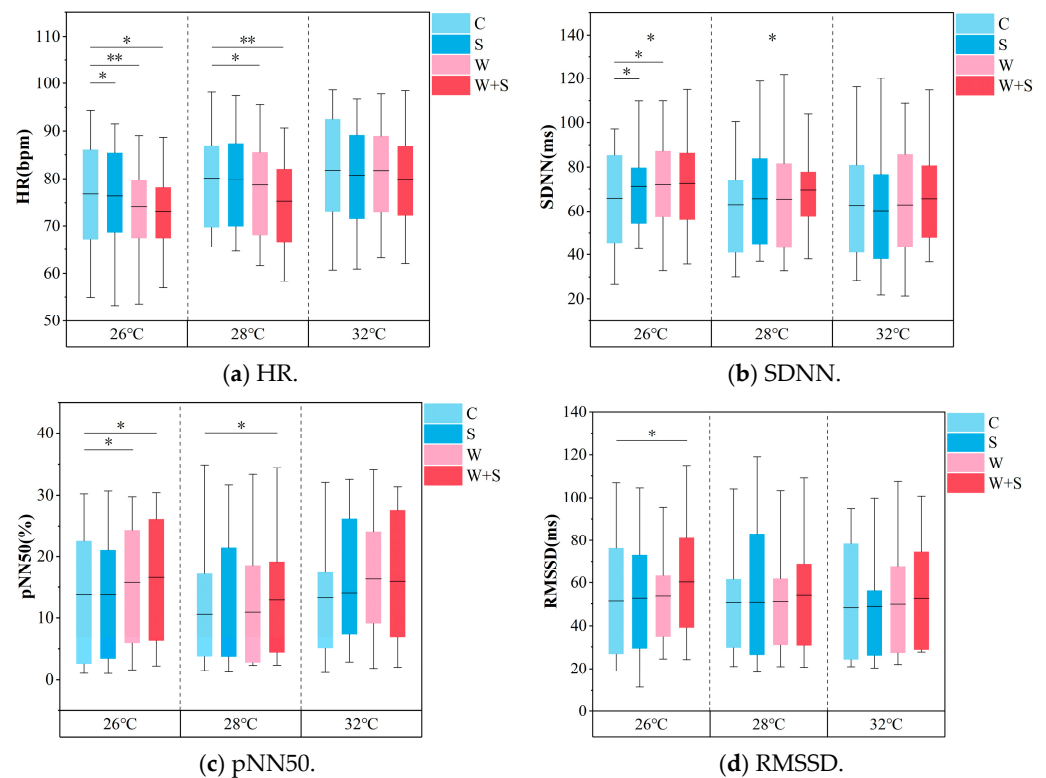


Figure 4. Heart rate variability of participants under different visual and auditory stimuli conditions at different operative temperatures. Note: * indicates $p < 0.05$, and ** indicates $p < 0.001$.

Figure 4b shows the changes in SDNN under different visual and auditory stimuli conditions at different operative temperatures. At 26 °C, compared to the control group C (65.86 ± 21.81 ms), exposure to any stimulus condition significantly increased SDNN, with the S group (71.22 ± 20.65 ms, $p = 0.045$), the W group (71.97 ± 22.01 ms, $p = 0.030$), and the W + S group (72.51 ± 22.7 ms, $p = 0.017$) showing significant increases. The W + S group had the greatest increase. At 28 °C, the SDNN in the control group decreased to 64.28 ± 28.59 ms, and only the W + S group (69.59 ± 21.54 ms, $p = 0.046$) showed a significant increase compared to the control group. At 32 °C, although the W + S group (65.67 ± 21.71 ms) showed an upward trend compared to the control group (C: 62.74 ± 27.74 ms), no significant differences were observed between the groups ($p > 0.05$).

Figure 4c shows the changes in pNN50 under different visual and auditory stimuli conditions at different operative temperatures. At 26 °C, compared to the control group (C: $13.84 \pm 10.87\%$), both the W ($15.72 \pm 10.36\%$, $p = 0.011$) and W + S ($16.55 \pm 10.31\%$, $p = 0.007$) groups showed significant increases in pNN50, while the S group ($13.83 \pm 10.17\%$) showed no significant change ($p > 0.05$). At 28 °C, the pNN50 of the W + S group ($13 \pm 10.04\%$, $p = 0.002$) was significantly higher than that of the control group C ($10.57 \pm 10.12\%$). At 32 °C, no significant differences in pNN50 were observed among the groups ($p > 0.05$).

Figure 4d shows the changes in RMSSD under different visual and auditory stimuli conditions at different operative temperatures. At 26 °C, the RMSSD of the W + S group (60.3 ± 28.02 ms) was significantly higher than that of the control group C (51.7 ± 28 ms, $p = 0.011$). At other operative temperature conditions, although the RMSSD of the experimental groups was slightly higher than the control group, no significant differences were found ($p > 0.05$).

3.1.2. Skin Conductance Level

Figure 5 shows the changes in skin conductance level (SCL) under different visual and auditory stimuli conditions at various operative temperatures. At 26 °C, compared to the control group C (22.36 ± 3.14 μ S), exposure to either single or combined audio-visual stimuli significantly reduced SCL, with the S group (21.5 ± 2.85 μ S, $p = 0.049$), W group (21.13 ± 3.02 μ S, $p = 0.024$), and W + S group (20.64 ± 3.06 μ S, $p = 0.011$), where the W + S group showed the greatest reduction. At 28 °C, although all experimental groups showed lower SCL than the control group C (22.82 ± 3.60 μ S), only the W + S group (21.47 ± 3.89 μ S, $p = 0.002$) reached statistical significance. However, at 32 °C, compared to the control group C (25.09 ± 4.21 μ S), both the S group (25.54 ± 4.75 μ S, $p = 0.015$) and the W group (25.92 ± 4.95 μ S, $p = 0.004$) showed significant increases.

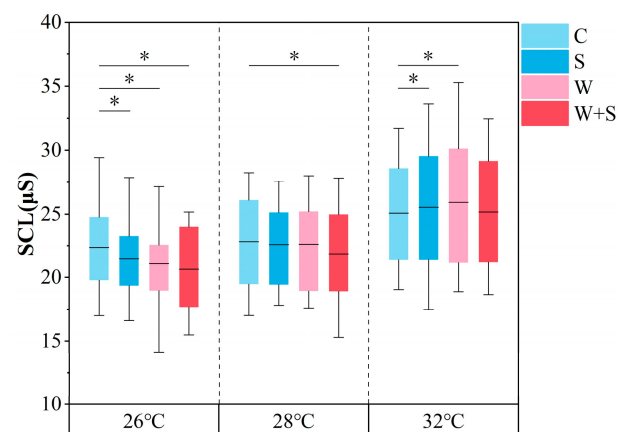


Figure 5. Skin conductance level of participants under different visual and auditory stimuli conditions at different operative temperatures. Note: * indicates $p < 0.05$.

3.1.3. Mean Skin Temperature

Figure 6 shows the changes in mean skin temperature (ST) under different visual and auditory stimuli conditions at various operative temperatures. At 26 °C, compared to the control group C (33.02 ± 0.69 °C), all experimental groups exposed to either single or combined audio-visual stimuli showed an upward trend in skin temperature. However, only the auditory stimulus group (33.37 ± 0.63 °C, $p < 0.001$) showed a statistically significant increase. At 28 °C and 32 °C, the S group, W group, and W + S group all exhibited significant increases in skin temperature compared to the control group ($p < 0.05$).

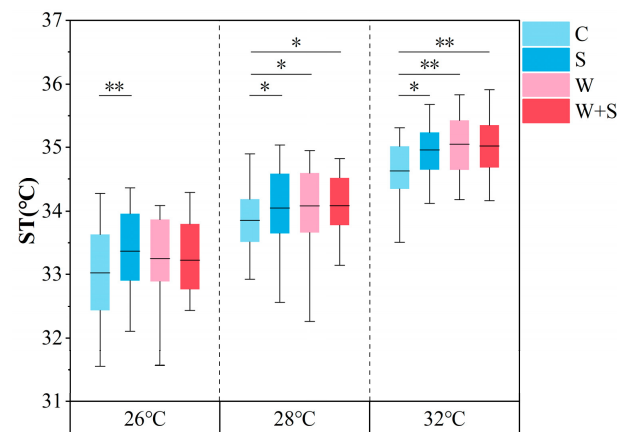


Figure 6. Mean skin temperature of participants under different visual and auditory stimuli conditions at different operative temperatures. Note: * indicates $p < 0.05$, and ** indicates $p < 0.001$.

3.1.4. Blood Pressure

Table 5 presents the changes in systolic blood pressure (SBP) and diastolic blood pressure (DBP) under different visual and auditory stimuli conditions at various operative temperatures. The results show that, across all operative temperature conditions, the SBP in the S group, W group, and W + S group was slightly lower than in the control group (C). Although this trend was consistent, the differences did not reach statistical significance ($p > 0.05$). Similarly, no significant differences were observed in DBP between the experimental groups and the control group.

Table 5. Blood pressure of participants under different visual and auditory stimuli conditions at different operative temperatures.

Operative Temperature		C	S	W	W + S
SBP	26 °C	103.65 ± 11.85	101.43 ± 10.2	102.05 ± 10.23	102.45 ± 10.14
	28 °C	101.41 ± 9.81	100.14 ± 10.53	100.61 ± 12.08	101 ± 10.8
	32 °C	101.70 ± 11.12	101.5 ± 8.58	101.39 ± 10.1	100.43 ± 12.41
DBP	26 °C	68.63 ± 7.4	69.33 ± 7.95	68.96 ± 7.13	69.62 ± 6.52
	28 °C	68.75 ± 7.58	68.52 ± 6.19	69.17 ± 6.75	68 ± 7.28
	32 °C	68 ± 6.91	67.91 ± 6.64	68.23 ± 6.98	67.04 ± 6.31

3.2. Psychological Response

3.2.1. Thermal Sensation and Thermal Comfort

Figure 7 shows the changes in thermal sensation (TSV) and thermal comfort (TCV) under different visual and auditory stimuli conditions at various operative temperatures. At 26 °C, compared to the control group C (0.02 ± 0.14), all experimental groups showed a significant decrease in TSV (S: -0.13 ± 0.11 , $p = 0.036$; W: -0.48 ± 0.17 , $p = 0.001$; W + S: -0.44 ± 0.26 , $p = 0.004$), with the W group showing the greatest reduction. Correspondingly, TCV significantly increased in all experimental groups, with S (0.79 ± 0.27 , $p = 0.015$), W (0.94 ± 0.19 , $p = 0.026$), and W + S (0.88 ± 0.29 , $p = 0.044$) all significantly higher than the control group C (0.59 ± 0.25). The W group showed the most pronounced improvement in both TSV reduction and TCV increase. At 28 °C, all experimental groups exhibited significant changes in both TSV and TCV compared to the control group C (TSV: 0.79 ± 0.18 ; TCV: 0.04 ± 0.13) ($p < 0.05$). Specifically, TSV decreased significantly across all stimulus conditions, and TCV increased significantly. The W group showed the most prominent effect, with a TSV decrease of 0.69 scale and a TCV increase of 0.38 scale. However, at

32 °C, neither TSV nor TCV showed significant differences between the experimental groups and the control group C ($p > 0.05$).

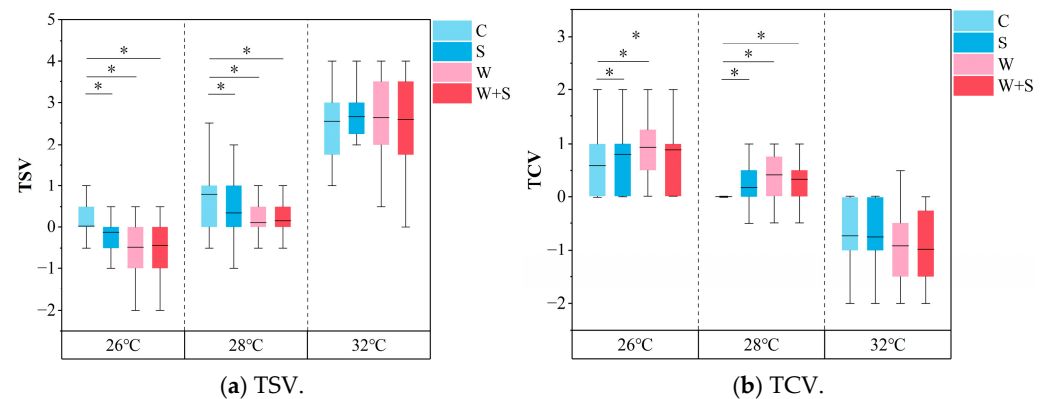


Figure 7. Thermal sensation and thermal comfort of participants under different visual and auditory stimuli conditions at different operative temperatures. Note: * indicates $p < 0.05$.

3.2.2. Visual Comfort

Figure 8 shows the changes in visual comfort (VCV) under different visual and auditory stimuli conditions at various operative temperatures. At 26 °C, compared to the control group C (0.40 ± 0.19), the auditory stimulus group S (0.50 ± 0.19) showed a slight increase, but the difference was not significant. However, the visual stimulus group W (0.71 ± 0.22 , $p = 0.018$) and the combined stimulus group W + S (0.75 ± 0.26 , $p = 0.005$) showed significant increases ($p < 0.05$). At 28 °C, all three experimental groups showed slight increases in VCV compared to the control group, but the differences did not reach statistical significance ($p > 0.05$). At 32 °C, the auditory stimulus group S (0.23 ± 0.11) showed almost no difference compared to the control group C (0.23 ± 0.14). The visual stimulus group W (0.35 ± 0.23) and the combined stimulus group W + S (0.42 ± 0.27) exhibited slight upward trends, but these differences were not statistically significant ($p > 0.05$).

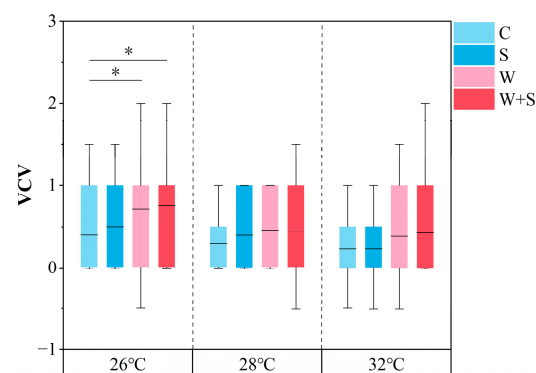


Figure 8. Visual comfort of participants under different visual and auditory stimuli conditions at different operative temperatures. Note: * indicates $p < 0.05$.

3.2.3. Acoustic Comfort

Figure 9 shows the changes in acoustic comfort (ACV) under different visual and auditory stimuli conditions at various operative temperatures. At both 26 °C and 28 °C, no significant differences in ACV were observed between the experimental groups and the control group ($p > 0.05$). At 32 °C, the auditory stimulus group S and the combined stimulus group W + S showed an increase of 0.21 in ACV compared to the control group C (0.25 ± 0.11), but this change did not reach statistical significance ($p > 0.05$).

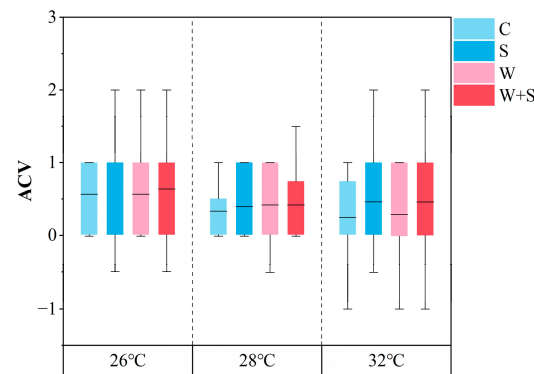


Figure 9. Acoustic comfort of participants under different visual and auditory stimuli conditions at different operative temperatures.

3.2.4. Sex Difference in Psychological Response

Because the sample was relatively balanced by sex, an exploratory sex-disaggregated analysis was conducted for the main subjective variables (TSV, TCV, VCV, and ACV). Overall, the results are presented in Table 6. Overall, no statistically significant differences were found between male and female participants under any experimental condition ($p > 0.05$). Descriptively, female participants tended to report slightly higher TSV values in most conditions, particularly at 28 °C and 32 °C. Female participants also showed somewhat higher VCV and ACV scores under several nature-based stimulus conditions, especially the W and W + S settings. However, none of these differences reached statistical significance.

Table 6. Sex difference in psychological response under different visual and auditory stimuli conditions at different operative temperatures.

Experimental Conditions		TSV		TCV		VCV		ACV	
		Male	Female	Male	Female	Male	Female	Male	Female
26 °C	C	0 ± 0.11	0.04 ± 0.16	0.59 ± 0.23	0.59 ± 0.17	0.34 ± 0.14	0.46 ± 0.24	0.54 ± 0.15	0.59 ± 0.21
	S	−0.29 ± 0.08	0.04 ± 0.23	0.67 ± 0.17	0.92 ± 0.26	0.38 ± 0.17	0.63 ± 0.31	0.38 ± 0.27	0.88 ± 0.31
	W	−0.42 ± 0.12	−0.54 ± 0.16	0.75 ± 0.28	1.13 ± 0.17	0.46 ± 0.24	0.96 ± 0.21	0.38 ± 0.23	0.75 ± 0.39
	W + S	−0.5 ± 0.07	−0.38 ± 0.13	0.79 ± 0.28	0.96 ± 0.31	0.59 ± 0.17	0.92 ± 0.39	0.38 ± 0.17	0.92 ± 0.37
28 °C	C	0.75 ± 0.17	0.83 ± 0.14	0 ± 0.22	0.09 ± 0.22	0.3 ± 0.19	0.3 ± 0.19	0.3 ± 0.23	0.38 ± 0.13
	S	0.29 ± 0.18	0.42 ± 0.12	0.17 ± 0.33	0.17 ± 0.15	0.34 ± 0.24	0.46 ± 0.25	0.34 ± 0.19	0.46 ± 0.29
	W	0 ± 0.24	0.21 ± 0.23	0.42 ± 0.41	0.42 ± 0.22	0.34 ± 0.29	0.59 ± 0.11	0.26 ± 0.24	0.59 ± 0.26
	W + S	0 ± 0.16	0.29 ± 0.24	0.34 ± 0.19	0.34 ± 0.15	0.3 ± 0.19	0.59 ± 0.27	0.17 ± 0.12	0.67 ± 0.33
32 °C	C	2.38 ± 0.28	2.71 ± 0.15	−0.71 ± 0.33	−0.75 ± 0.22	0.29 ± 0.25	0.17 ± 0.24	0.21 ± 0.28	0.29 ± 0.15
	S	2.54 ± 0.23	2.75 ± 0.22	−0.75 ± 0.29	−0.75 ± 0.12	0.21 ± 0.12	0.26 ± 0.24	0.17 ± 0.19	0.75 ± 0.25
	W	2.46 ± 0.16	2.79 ± 0.41	−0.88 ± 0.31	−0.96 ± 0.25	0.21 ± 0.19	0.5 ± 0.26	0.29 ± 0.31	0.29 ± 0.14
	W + S	2.38 ± 0.21	2.79 ± 0.36	−0.92 ± 0.26	−1.04 ± 0.25	0.25 ± 0.22	0.58 ± 0.27	0.25 ± 0.22	0.67 ± 0.26

4. Discussion

4.1. Restorative Effects of Visual and Auditory Stimuli

4.1.1. Physiological Response

To control for the confounding effects of temperature, this section focuses on physiological responses under the neutral condition of 26 °C. According to the results in Section 3.1, Figure 10 shows the changes in physiological indicators under the three types of stimuli compared to the control group at 26 °C. The results show that all three stimulation conditions promoted recovery in heart rate variability and skin conductance indices to varying degrees. However, there were no significant effects on blood pressure or skin temperature. The restorative effects ranked as follows: combined audio-visual stimuli group (W + S) > visual stimuli only group (W) > auditory stimuli only group (S). Specifically,

compared to the control group (C), the W + S group showed a 6.08% reduction in heart rate (HR), a 10.09% increase in SDNN, a 19.59% increase in pNN50, and a 7.68% decrease in skin conductance level (SCL). The magnitude of changes in the W and S groups was lower in comparison. As quantified by Cohen's *d* values in Table 7, effect sizes were greatest in the W + S group, underscoring the enhanced efficacy of combined audio-visual stimuli in promoting physiological restoration.

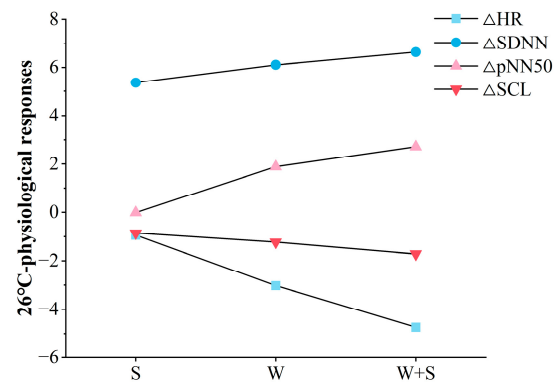


Figure 10. Physiological response changes under different visual and auditory stimuli at 26 °C.

Table 7. Cohen's *d* values of each group under different stimuli conditions at 26 °C.

	HR	SDNN	pNN50	SCL
C-S	0.64	−0.509	−0.216	0.443
C-W	0.935	−0.579	−0.729	0.492
C-W + S	0.93	−0.673	−0.814	0.596

These results align with previous findings, confirming that exposure to natural visual and auditory stimuli can support physiological recovery. According to the Stress Recovery Theory proposed by Ulrich et al. [69], natural environments can quickly reduce negative emotions and activate the parasympathetic nervous system, thereby promoting physiological relaxation. Meanwhile, the Attention Restoration Theory [70] suggests that the “soft fascination” characteristics of natural environments help restore attentional resources and alleviate mental fatigue caused by cognitive load.

It is particularly noteworthy that the combined audio-visual condition yielded the most pronounced improvements across multiple physiological indicators, surpassing those observed with unimodal stimuli. This suggests a potential advantage of multisensory integration in restoration mechanisms. When a person receives coordinated visual and auditory inputs, relevant brain regions (such as the superior temporal sulcus, limbic system, and parietal association cortex) integrate the information, which enhances perceptual stability and immersion [71]. Compared to single stimuli, combined audio-visual input improves the efficiency of attentional resource use, more easily evokes emotional resonance, and further enhances the response of the parasympathetic nervous system. This helps the body enter a state of relaxation and recovery.

In summary, under optimal thermal conditions, natural visual and auditory stimuli, especially in combination, can significantly enhance heart rate variability and reduce stress-related physiological indicators such as skin conductance, showing great potential for physical and mental restoration.

4.1.2. Psychological Response

According to Section 3.2, under the neutral condition of 26 °C, natural visual and auditory stimuli not only exhibited significant regulatory effects on physiological indi-

cators, but also promoted psychological restoration. Figure 11 illustrates the changes in psychological indicators under the three types of stimuli compared to the control group, including thermal sensation, thermal comfort, visual comfort, and acoustic comfort.

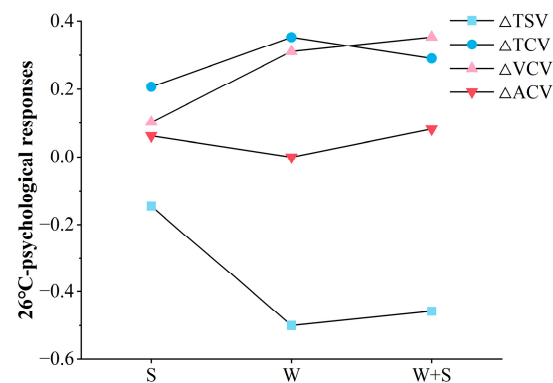


Figure 11. Psychological response changes under different visual and auditory stimuli at 26 °C.

For thermal sensation and thermal comfort, all three types of stimuli improved participants' subjective thermal experience to some extent. TSV was significantly reduced, while TCV increased significantly, indicating that natural elements enhanced individuals' comfort perception in a neutral thermal environment. In terms of the magnitude of improvement, the visual stimuli only group (W) showed the greatest effect, followed by the combined audio-visual stimuli group (W + S), with the auditory stimuli only group (S) showing the weakest effect. Specifically, compared to the control group (C), TSV in W, W + S, and S groups decreased by 0.50 scale, 0.46 scale, and 0.15 scale, respectively, while TCV increased by 0.35 scale, 0.29 scale, and 0.20 scale, respectively. These results suggest that visual stimuli are more sensitive than auditory stimuli in modulating thermal perception, particularly due to factors such as cool colors, greenery, and a sense of spatial openness in natural landscapes. Such visual features tend to evoke associations with cooler environments, thus alleviating the psychological load caused by thermal conditions. In contrast, auditory stimuli mainly regulate emotions, but lack a direct association with temperature, making it difficult to provide a psychological cue for thermal perception.

For visual comfort, the combined audio-visual stimuli group showed the highest improvement, followed by the visual stimuli only group, while the auditory stimuli only group showed the weakest effect. This indicates that visual input is key to enhancing visual comfort, while the addition of sound further strengthens the sense of immersion and harmony in the environment, resulting in a more positive experience. Previous studies have shown that when visual and auditory stimuli are consistent in context, they can significantly enhance perceptual integration and subjective pleasantness of the environment [72], and our findings provide empirical support for this view.

For acoustic comfort, the combined audio-visual stimuli group and the auditory stimuli only group had similar effects, both superior to the visual stimuli only group. This result suggests that improvement in acoustic comfort mainly depends on the presence of sound, while visual stimuli alone are insufficient to enhance auditory experience.

In summary, Visual stimuli exert a more direct and stronger effect on thermal perception and visual comfort, while auditory stimuli primarily improve the auditory dimension. Combined audio-visual stimuli enhance the overall sense of immersion and perceptual coherence, further improving subjective pleasantness. These results provide theoretical and practical guidance for multisensory-oriented healthy environment design.

4.2. The Effect of Temperature on the Restorative Effects of Visual and Auditory Stimuli

This section explores the impact of different operative temperature conditions on the restorative effects of natural visual and auditory stimuli. According to the experimental results presented in Section 3, both 26 °C and 28 °C, within the thermal comfort range, exhibited superior performance across most physiological and psychological indicators compared to the control group, showing significant restorative effects with statistical significance.

In terms of physiological restoration, the recovery effects in the neutral 26 °C environment were generally stronger than in the warmer 28 °C environment, especially in indicators reflecting autonomic nervous system activity. This suggests that under 26 °C, natural visual and auditory stimuli are more beneficial in activating the parasympathetic nervous system and promoting physiological relaxation. In contrast, at 28 °C, although still within the thermal comfort zone, the improvement in some physiological indicators was attenuated, indicating that when environmental temperature deviates from the thermal neutral point, the restorative effects of natural stimuli may be somewhat suppressed.

Regarding psychological restoration, the temperature also influenced the restoration of thermal sensation and comfort. Specifically, at 28 °C, participants experienced a slightly greater decrease in TSV compared to 26 °C, while the thermal comfort TCV increased less or at a similar rate. This suggests that in warmer environments, the cooling cues provided by natural stimuli may be more easily detected, but due to the overall higher thermal load, the improvement in subjective comfort is limited.

However, when the operative temperature increased to 32 °C, no significant differences were observed between the experimental groups and the control group in most physiological and psychological indicators, indicating that the restorative effects of natural visual and auditory stimuli were markedly suppressed in high-temperature environments. Previous studies have shown that when environmental temperature exceeds the human thermal adaptation threshold, parasympathetic nervous activity is significantly inhibited [73], thus reducing the ability of natural stimuli to regulate the autonomic nervous system. In such conditions, while natural visual and auditory stimuli may still offer emotional relief, the physiological load induced by high temperatures may dominate the individual's attention resources, hindering the positive perception and internal effects of the stimuli.

It is noteworthy that, at 32 °C, both the visual stimuli group and the auditory stimuli group showed a significant increase in skin conductance level (SCL) compared to the control group. Unlike the typical "relaxation → decrease in SCL" trend seen in previous studies, this increase may be due to enhanced sweat gland secretion. The increased moisture on the skin surface caused by high temperatures could mask the regulatory effect of natural stimuli on SCL. Therefore, under the 32 °C condition, SCL should be interpreted more cautiously, as it may primarily reflect thermos physiological stress rather than restorative status. This suggests that under severe heat exposure, the physiological load imposed by the thermal environment may override or mask the restorative benefits of natural visual and auditory stimuli. Regarding skin temperature (ST), no significant difference was observed in the W and W + S groups at 26 °C compared to the control group, which may be due to the body's natural temperature regulation being stable in a thermally neutral environment. However, at 28 °C and 32 °C, ST in all experimental groups significantly increased. Elevated skin temperature is a normal thermoregulatory response to warm environments, involving peripheral vasodilation to facilitate heat dissipation [74]. Additionally, the electronic window display devices used for visual stimuli may emit small amounts of radiant heat during operation [75]. In contrast to other physiological indices such as HR and SCL, which decreased under natural stimulus conditions and are typically interpreted as indicators of relaxation, ST increased. This divergence suggests that ST may

not align with restorative patterns under warm conditions, and its interpretation is further complicated by the presence of potential local heat sources. Future studies should employ separate measurements of local skin temperature near the display device and at distal sites to better isolate the effects of radiant heat from thermoregulatory responses.

In conclusion, this study found that natural visual and auditory stimuli have significant physiological and psychological restorative effects in moderate thermal environments (26 °C and 28 °C), with the effects being more stable in the neutral environment of 26 °C. In contrast, at 32 °C, the restorative effects of natural visual and auditory stimuli were significantly weakened, with some physiological indicators even showing an opposite trend. This suggests that environmental temperature is an important factor influencing the effectiveness of natural stimuli. Therefore, when designing multisensory environments, it is crucial to consider the impact of temperature and adjust intervention strategies for different thermal conditions to ensure that visual and auditory stimuli have the maximum benefit within the target temperature range. Especially in high heat stress situations, the limits of traditional visual and auditory interventions should be recognized, and additional cooling measures should be considered to ensure human comfort and health. This study adds to the understanding of the differences in the restorative effects of natural visual and auditory stimuli in various thermal environments, providing a theoretical foundation for future effective health support strategies and multisensory intervention mechanisms in high-temperature urban settings.

4.3. Correlations Among Subjective Parameters

Building on the established physiological and psychological restorative effects of natural visual and auditory stimuli, this study further investigated the relationships among different subjective perception parameters. Specifically, the correlations among thermal sensation (TSV), thermal comfort (TCV), visual comfort (VCV), and acoustic comfort (ACV) were analyzed under different thermal environmental conditions. Figure 12 presents the correlations among these four subjective indicators at 26 °C, 28 °C, and 32 °C.

The results show that, in the neutral environment of 26 °C, there was a negative correlation trend between TCV and TSV, but this was not statistically significant. This may be due to the small variation in thermal sensation among participants under neutral conditions, leading to relatively concentrated subjective experiences and minimal individual differences, which weakens the statistical correlation between thermal comfort and thermal sensation. However, as the operative temperature increased to 28 °C and 32 °C, a significant negative correlation emerged between TCV and TSV, with correlation coefficients of -0.63 and -0.83 , respectively. This indicates that in warmer and high-temperature environments, individuals exhibit greater sensitivity and variability in their subjective responses to thermal stimuli, and the negative relationship between thermal comfort and thermal sensation becomes more pronounced.

Further analysis revealed that, under all operative temperature conditions, TCV was significantly positively correlated with both VCV and ACV. This suggests that subjective thermal comfort is jointly influenced by visual and auditory factors. The correlation coefficients between TCV and VCV were consistently higher than those between TCV and ACV, indicating that visual perception plays a stronger role in shaping individual thermal comfort. This finding is consistent with the analysis in Section 4.1, which highlighted the greater sensitivity of visual stimuli in modulating thermal sensation. Moreover, as temperature increased, the correlation coefficients between TCV and VCV, as well as TCV and ACV, both showed a declining trend. This suggests that the influence of multisensory perception on thermal comfort may diminish in high-temperature environments.

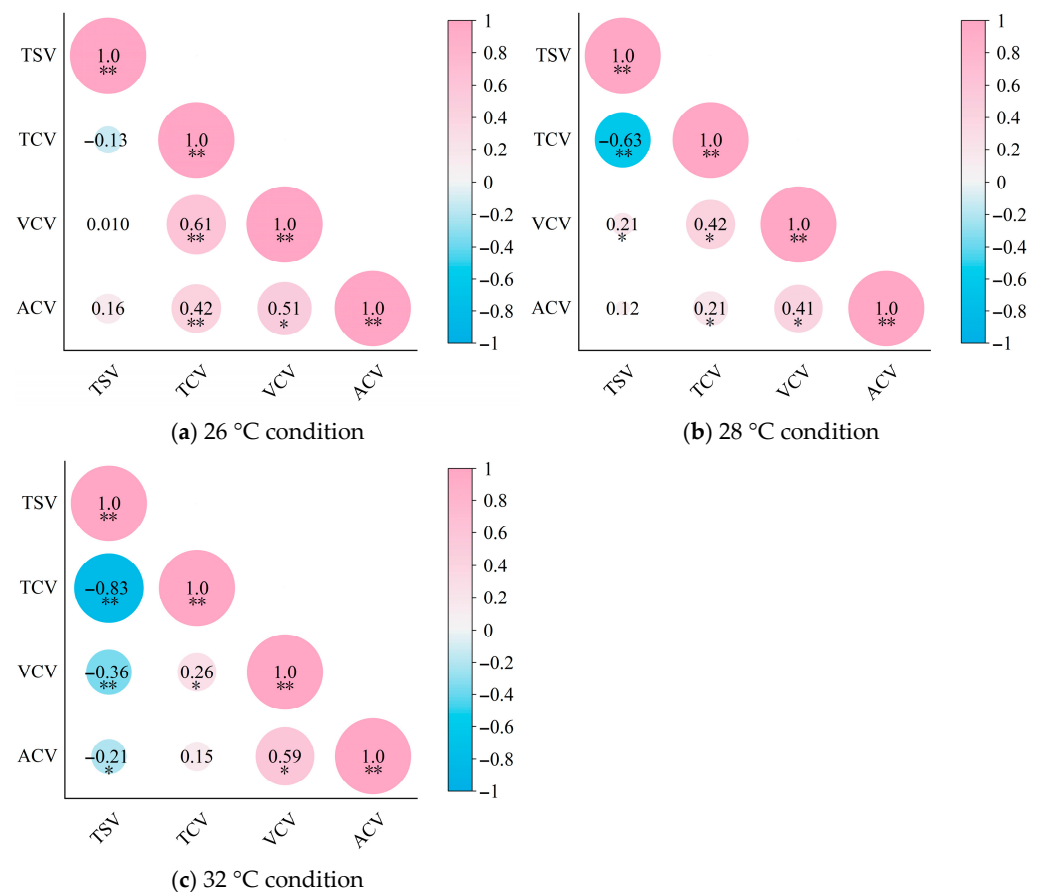


Figure 12. Correlations among subjective parameters under different operative temperature conditions. Note: * indicates $p < 0.05$, and ** indicates $p < 0.001$.

In summary, this study demonstrated significant perceptual correlations among thermal sensation, thermal comfort, visual comfort, and acoustic comfort. Visual comfort had a more direct and pronounced positive effect on thermal comfort, while acoustic comfort may indirectly improve thermal comfort by enhancing visual perception or overall environmental pleasantness. These findings provide a theoretical basis for the integrated design of multisensory environmental interventions and emphasize the importance of properly configuring visual and auditory elements in building and urban space design to achieve optimal overall comfort.

4.4. Limitations

This study has several limitations. First, it focused on immediate responses within a short duration (15 min) and did not address the effects or sustainability of repeated or long-term exposure. Previous studies have shown that the positive impact of contact with nature may accumulate and strengthen with increased frequency and duration of exposure, due to cumulative and temporal characteristics [76]. Therefore, future research could adopt longitudinal or repeated intervention designs to explore the sustainability and time sensitivity of the restorative effects. Second, the temperature range was limited to three levels (26 °C, 28 °C, and 32 °C), and the relative humidity was maintained at 60–70%. While this humidity range reflects local summer conditions in Changsha, it limits generalizability to strictly humidity-controlled environments. Future studies should explore a wider range of thermal conditions. Third, vertical air temperature gradients were not measured at multiple heights. Given the low and stable air velocity (consistently below 0.1 m/s) and symmetrical seating arrangement, the risk of significant vertical gradients causing local

discomfort was minimal. Fourth, formal calibration certificates with traceability to national or international standards were not available for all devices. The DS1922L skin temperature sensors have an accuracy of ± 0.5 °C, which does not meet the ± 0.1 °C requirement of ISO 9886 [77]. Therefore, only qualitative conclusions can be drawn from skin temperature comparisons. Fifth, a single lighting condition was used (CCT 5200 K, illuminance 400 lx). While these settings are representative of typical office lighting in China, different lighting conditions may interact with natural stimuli and thermal perception in ways not captured here. Future studies should systematically investigate such interactions. Finally, the participant cohort was limited to 24 young, healthy adults from Changsha, China, and the stimuli were restricted to a single green landscape and birdsong at 45 dB (A). These constraints limit generalizability to broader populations and diverse natural environments. Future studies should include more diverse samples and stimulus sets.

5. Conclusions

This study systematically investigated the effects of natural visual and auditory stimuli on individual physiological and psychological restoration under different operative temperature conditions (26 °C, 28 °C, and 32 °C). The main qualitative conclusions are as follows:

(1) Natural visual and auditory stimuli effectively promoted physiological restoration in neutral temperature environments. Under moderate thermal conditions (26 °C and 28 °C), the visual stimuli only group, auditory stimuli only group, and combined audio-visual stimuli group all showed significant improvements in multiple physiological indicators compared to the control group. Among them, the combined audio-visual stimuli group demonstrated the most pronounced physiological restoration effect. At 26 °C, compared with the control group, the combined group reduced heart rate by 6.08%, increased SDNN and pNN50 by 10.09% and 19.59%, and reduced skin conductance level by 7.68%.

(2) Visual stimuli had a more significant effect on improving subjective thermal sensation (TSV) and thermal comfort (TCV). At 26 °C, compared with the control group, the visual stimuli group reduced TSV by 0.50 scale and increased TCV by 0.35 scale. Auditory stimuli were most effective in improving acoustic comfort (ACV), but had limited effects on TSV and TCV. Combined audio-visual stimuli exhibited a synergistic effect on visual comfort (VCV), showing the greatest improvement compared to the control group, and significantly enhancing immersion and environmental pleasantness.

(3) The restorative effects were significantly modulated by ambient temperature. As the operative temperature increased from 26 °C to 28 °C and then to 32 °C, the positive effects of natural visual and auditory stimuli on physiological and psychological restoration gradually declined. In the high-temperature environment of 32 °C, most physiological and psychological restoration indicators showed no significant difference from the control group, and some physiological responses, such as SCL, even increased, showing a “reverse” trend.

(4) Significant correlations were observed among subjective comfort perception indicators. TCV was positively correlated with both VCV and ACV, with the correlation coefficient between TCV and VCV higher than that between TCV and ACV. As the temperature increased from 26 °C to 28 °C and then to 32 °C, both the TCV–VCV and TCV–ACV correlations weakened. In addition, in non-neutral environments, there was a more pronounced negative correlation between TCV and TSV.

This study systematically explores the restorative effects of natural auditory and visual stimuli under different temperatures, providing theoretical support for multisensory mechanisms in thermal environments and scientific evidence for healthy living environment

design. The findings are important for advancing restorative environment theory and improving public health.

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