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Goal-Directed Human Factor Experiment on the Non-Visual Effect of Luminous Environment on Indoor Exercise

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Abstract: Currently, research on the application of luminous environments in exercise is limited. This study addresses this gap by simulating a badminton game through somatosensory games streamed on television within a laboratory, where different luminous environments were established. A total of 40 participants, comprising 22 males and 18 females aged between 18 and 50 years, participated in the experiment. The exercise process encompasses six stages: resting 1, warming up, exercising 1, resting 2, exercising 2, and relaxing, with a total duration of approximately one hour. Throughout the experiment, continuous measurement of heart rate (HR), skin conductance level (SCL), and electroencephalogram (EEG) data were recorded. Additionally, participants completed the Positive and Negative Affect Schedule (PANAS) and the Karolinska Sleepiness Scale (KSS) during the warming-up and relaxing stages. The results indicate correlations between physiological and psychological responses and the luminous environment at different stages of exercise. This study empolys a multidisciplinary approach, integrating concepts from architectural optics, sports psychology, and exercise physiology. By simulating exercise in different lighting environments through a combination of real light environments and somatosensory interaction technology, it offers an innovative solution for conducting controlled lighting experiments in indoor settings. Furthermore, a parameter system for the light environment in indoor fitness exercises has been established, providing a theoretical foundation and data support for constructing a "human-centered" fitness lighting environment.

1. Introduction

In the field of light environment research, international academic organizations represented by CIE have achieved numerous accomplishments in the study of healthy light environments. Notably, in 2002, Berson et al. from Brown University identified the third type of photoreceptor cells, the "ganglion cells" (ipRGCs) [1], initiating research into the influence of light on human physiology and psychology. An increasing body of evidence suggests that the light environment regulates the human biological clock rhythm and impacts aspects such as mood, sleep quality, alertness, and even health [2-6]. A favorable indoor light environment can promote physical and mental well-being and enhance efficiency, while suboptimal lighting can result in visual fatigue, lack of concentration, and even trigger health issues like headaches and sleep disorders [7-9].

Research indicates that in addition to exerting a certain regulatory effect on human visual responses, these photoreceptor cells, more importantly, regulate the human biological clock rhythm and impact factors such as mood, sleep quality, alertness, and even health through non-visual neural pathways [10-12]. Manuel Spitschan's research indicates that melanopsin, located in the intrinsically photosensitive retinal ganglion cells, plays a critical role in non-image-forming visual functions. It regulates a variety of physiological and behavioral responses unrelated to image formation, such as pupil size adjustment, melatonin suppression, circadian rhythm synchronization, and alertness modulation [13]. Currently, numerous achievements have been achieved in exploring on the non-visual effects of indoor light environments within architectural scenarios such as offices, classrooms, and hospital wards. These studies predominantly focus on real environments or the establishment of simulated scenarios combined with human factor experiments, in

conjunction with other statistical methods, to elucidate the intrinsic patterns of indoor light environment changes in enhancing work and learning efficiency, alleviating anxiety, boosting vitality, and improving sleep and depressive moods [14-17]. Their common characteristic is that the subjects have limited activity within the architectural space and relatively stable scenes within their field of vision, facilitating the collection of accurate human factor experiment data. In contrast, within the context of fitness and exercise, the subjects exhibit high levels of activity and significant variations in their vision environments. The acquisition of human factor experiment data is prone to be influenced by the subjects' movements, and given that most fitness and exercise activities require substantial space, constructing simulated scenarios incurs high costs. Consequently, there is a scarcity of research on the non-visual effects of indoor light environments in fitness and exercise scenarios.

Constrained by technological limitations in previous studies, experiments were typically conducted in actual settings or through custom observation rooms and architectural scale models to address the requirements of such complex scenarios. Peijun Wen et al. [18] conducted experiments in a water sports center, investigating the performance of 14 elite athletes in light environments with different color temperatures but the same illuminance. The findings revealed that, compared to the controlled condition light environment (1020 lx/5780 K), the experimental light environment (1020 lx/8512 K), resulted in faster reaction speeds, fewer errors, and increased swimming speeds among the athletes. This study solely on comparing two color temperature scenarios, indicating that a higher color temperature is beneficial for improving athletic performance, without exploring the potential impact of illuminance on athletes. Nevertheless, existing research has verified that illuminance also affects alertness, thereby influencing human athletic performance. The experiments were carried out in a genuine water sports center, providing authentic experiences for the subjects and yielding more precise and scientific experimental data. However, for such complex scenarios,

implementation in real environments presents significant challenges. To meet the demands of special experimental scenarios, an equivalent observation model was constructed based on the characteristics of human visual fields. Through the use of a custom observation room, it was discovered that, under identical illuminance and chromaticity conditions, there were significant generational differences in the perception of brightness induced by light stimulation. Mojtaba Parsaee et al. [19] utilized a 1:50 architectural scale model to validate the regulatory role of building shading components on photobiological effects and disclose the relationship between different parameters of the shading board and non-visual effects. Although such models can effectively replicate the visual characteristics of the real environments, the subjects' experience is suboptimal, potentially leading to deviations in the experimental results. It is noteworthy that the majority of the aforementioned studies focused on the influence of spectral characteristics, with insufficient attention given to the interaction mechanisms of illuminance parameters.

With the revolutionary development of virtual reality technology, the integration of VR with human factor experiments has paved new avenues for studying complex scenarios. Wong et al. selected a lecture hall at the University of Hong Kong as the research object, developed a BIM model and independently constructed the lighting equipment to facilitate user interaction. The BIM model was exported as FBX and IFC files for texture mapping in 3ds Max and combined with DIALux to accomplish precise light distribution calculations. Ultimately, an immersive VR scene construction and interactive design were realized on the Unity platform. Upon verification, users were able to experience the lighting effect realistically and provide feedback through sensory means to enhance the design. This technology effectively enhanced the physical authenticity of the VR-simulated light environment, enabling participants to evaluate the design through multiple sensory channels (visual perception, spatial cognition). However, the research focused on collecting subjective feedback, and a monitoring system for objective indicators has not

yet been established. Mahmoudzadeh et al. [20] employed VR to construct an office environment with different light environments, where subjects were required to complete tests and questionnaires. The results indicated that compared with the traditional manual light control mode in the physical scene, subjects exhibited superior cognitive and task performance and achieved greater energy-efficient than the fully manual light control mode. While the fully automatic light control mode excelled in energy efficiency, it struggled to meet the requirements of scholars such as Li Xiaojun [21]. They innovatively combined the virtual driving scene with brain-computer interface technology, systematically analyzed the neural response mechanism of driver attention to the light source color temperature, processed the data to obtain the attention growth rate and reaction time, and determined the optimal tunnel light source color temperature through data analysis. VR technology significantly improves the validity of experiments through multi-sensory immersive experiences. Its core advantages include: (1) supporting the precise reproduction of complex dynamic scenes; (2) offering a relatively authentic experience for subjects; and (3) enhancing the authenticity of subjects' behavioral responses. Nevertheless, it is important to note that current VR technology still faces technical limitations in accurately simulating of illumination parameters, thereby hindering the precise replication of light environments. Advancements in intelligent sensing technology have introduced multi-dimensional data collection solutions for human factor experiments. Wearable devices enable continuous monitoring of physiological parameters, electroencephalogram devices capture neural cognitive activities, and eye-tracking systems analyze visual attention mechanisms, etc. [22-25]. These technological breakthroughs inspire this experiment and render the study of the non-visual effects of fitness exercises feasible.

This study integrates the above research methods and constructs an experiment of "real light environment + somatosensory interaction technology". Badminton was chosen as the experimental exercise, and a sports

field was established within the laboratory using large-screen projection and body-sensing interaction technology to approximately simulate the exercise process. An intelligent dimming system was utilized to freely regulate the illuminance and color temperature. The experimental design adopted a strategy of verification using both objective and subjective indicators: in the objective dimension, physiological stress states were characterized by heart rate (HR), skin conductance level (SCL), and electroencephalogram (EEG); in the subjective dimension, the Positive and Negative Affect Schedule (PANAS) and the Karolinska Sleepiness Scale (KSS) were employed to assess psychological perception and subjective sleepiness. The research focused on: 1) revealing the correlation between light environment parameters and both subjective and objective psychological and physiological indicators and 2) proposing threshold values for safe and comfortable light environment parameters for indoor fitness exercises. The research outcomes will create a light environment that promotes excellent exercise performance and provides an evidence-based foundation for designing future exercise spaces.

2. Method

2.1 Experimental design

A healthy indoor luminous environment should both meet the demand for visual health features and consider the circadian rhythms and emotional well-being of the users. The majority of current studies focus primarily on visual demands and health-related features, with luminous environment designs mainly aimed at meeting the standards of daylighting and illumination. Although relevant studies on sports science have reported that the changes in the luminous environment during exercise can influence various vital signs, including hormone level, heart rate, and temperature, which further affect performance, emotion, and comfort, most of the current results were obtained through qualitative analysis [26-29]. Based on the research results of sports science on the physiological and psychological performance in different exercising stages, this study aims to explore the impact of indoor luminous

environment changes, revealing a range of luminous environment parameters on improving positive emotions, enhancing exercise outcomes, and increasing alertness during physical activity.

(1) Optimizing warming-up outcomes: Warming up is a crucial adaptive process that transitions the body from a resting state to an active exercise state. It effectively prevents athletic injuries, improves exercise performance, and enhances psychological preparation [30-32]. Surveys suggest that average fitness enthusiasts report a warming-up duration ranging from 5 to 10 minutes, often with less emphasis compared to professional athletes. The warming-up exercise strength in this study was selected according to the recommendations of the American College of Sports Medicine (ACSM), reaching 50%-60% of maximum heart rate (approximately 90-120 bpm) and a reduced α wave power percentage. The study simulated distinct luminous environments to assess their effects on optimizing warming-up outcomes within appropriate warming-up procedures.

(2) Improve athletic performance: During the primary exercising stage, lasting for approximately 15-30 minutes before the recovery phase, maintaining a certain level of alertness and cognitive capability influences the exercising performance. Associated studies indicate that heightened alertness can improve response speed and exercise performance while reducing lapses, ultimately contributing to greater fulfillment, confidence, and motivation indirectly [33-35]. This study employs the Karolinska Sleepiness Scale (KSS) combined with electroencephalogram analysis to evaluate the degree of drowsiness and brain activity. The goal is to establish a correlation between a luminous environment and alertness in the exercising state.

(3) Mitigating fatigue: Appropriate mitigation of fatigue could effectively maintain a favorable exercise state and psychological well-being, thus contributing to overall physical and neurological health, thereby maximizing exercise benefits [36, 37]. Skin conductance level (SCL) is a reliable physiological indicator of fatigue, typically increasing during exercise.

(4) Enhancing emotional state: Numerous studies have confirmed that luminous environments can regulate emotions and moods to some extent. Positive emotions enhance motivation and engagement, resulting in a better exercise performance [38]. Both objective emotions and subjective feelings should be considered during the experiment to comprehensively evaluate emotional responses, which were measured by PANAS and electroencephalogram in this study.

(5) Facilitating relaxation: After exercising, individuals require relaxing activities to transform from an active state to a passive state, characterized by a gradual decrease in heart rate, reduced brain activity, and improved α-wave power. The bodies are restored to a peaceful state, which enhances the recovery of physical function and psychological health. Regulation of luminous environments can accelerate this recovery process.

2.2 Experiment preparation

(1) Testing ground and equipment: The experiment was performed in a laboratory without illumination or daylight, featuring an open space measuring 5m × 6 m. Based on a preliminary survey, badminton was selected as the experimental sport due to its relative ease of learning, high activity level, popularity among participants, and the substantial proportion of venues available for it. Participants engaged in a somatosensory game projected onto a large-screen television and simulated the badminton experience. To monitor physiological and psychological responses, participants were equipped with ErgoLab intelligent sensor wristbands and a wearable 16-channel EEG device. Artifact detection was automatically performed using ErgoAI on a proprietary device developed by Beijing Jinfa Technology Co., Ltd. Artifact-contaminated segments were identified by classifiers such as Support Vector Machine (SVM) and Random Forest, followed by the removal of EEG artifacts. Each participant was instructed to stand approximately 2 meters away from the screen within the laboratory while performing exercise tasks (Figure 1). Natural light was simulated through full-spectrum LED with adjustable illuminance and color

temperature [19]. HR and SCL were continuously monitored in real-time during the exercise, alongside simultaneous EEG signal recording. The experiment lasts approximately 1 hour, enabling the analysis of how different luminous environments impact physiological responses and psychological states.

Figure 1. The experimental environment

(2) Luminous environment construction: The luminous environment was established based on the illuminance and color temperature data retrieved from associated standards on the indoor luminous environment of sports facilities and survey data from indoor fitness environments. The study set four illuminance levels and three colors temperature levels derived from previous research [39-41]. The illuminance levels are 200 ± 10 lx, 500 ± 15 lx, 800 ± 20 lx, and 1000 ± 25 lx, while the color temperature levels are 3000 ± 150 K, 5000 ± 200 K, and 6500 ± 250 K. Meanwhile, to maintain consistent color rendering quality, the color rendering index in all scenarios should not fall below 65. The correspondence between illuminance and color temperature was designed based on the characteristics of natural lighting as well as the previous findings of Bao et al. Compared with 2000 lx, 3000 K, and 300 lx, 6000 K, individuals experience more positive emotions under 2000 lx, 6000 K, and 300 lx, 3000 K [31]. These results suggest that higher illuminance pairs well with higher color temperature, while lower illuminance pairs well with

lower color temperature. Thus, five luminous environment scenarios were established based on the previous correspondence relationship (Table 1).

Table 1. Luminous environment scenarios

Number	1	2	3	4	5
Parameters	200 lx/3000 K	500 lx/5000 K	800 lx/5000 K	800 lx/6500 K	1000 lx/6500 K

(3) Measured parameters

In the experiment, the parameters were measured following the lighting guidance of modern sports stadiums. Data was collected at 1.5 meters, corresponding to the participant's eye level. A Konica Minolta CL-500A spectroradiometer was utilized in the experiment. The illuminance and color temperature parameters in the laboratory were regulated to meet the demands listed in various luminous environments of Table 1, with deviations no greater than 5%. Due to the variations in laboratory space size, the illuminance in the actual environment at the human eye level may differ slightly from set parameters. Therefore, according to the visual characteristics of badminton, the illuminances were taken near the participants' eyes. Based on the principle of visual ergonomics, a three-dimensional coordinate system was established at the midpoint of the subject's eye socket (Figure 2), and illumination parameters were taken under the conditions of 45° upward, 0° horizontal, and 45° downward. The measurement positions are shown in Figure 2 [42]. The experimental luminous parameters obtained from different luminous environment design parameters and actual measured values near the eye are shown in Figure 3.
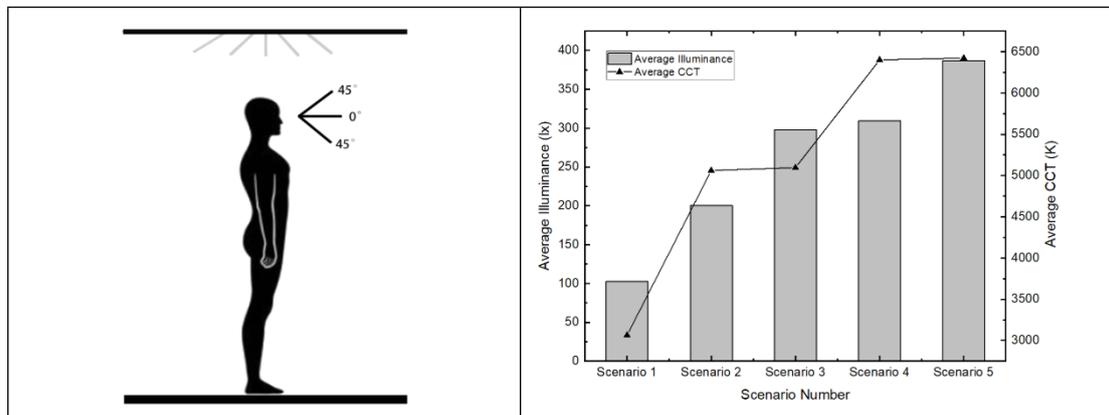
Figure 2. The measurement positions	**Figure 3**. Average luminous parameters at eye level

(4) Participants

A total of 40 participants were recruited for the experiment, including 22 males and 18 females aged from 18 to 50. No participants showed severe visual impairments apart from mild shortsightedness or longsightedness, which were corrected by wearing glasses. To ensure the accuracy, the experiment, the physical and mental conditions of the participants were assessed and screened. Participants were required to obtain sufficient sleep 24 hours prior to the experiment and to abstain from drug or alcohol consumption. Considering the sensitivity of the human biological clock to light, participants were instructed 14 days to maintain a consistent lifestyle, including regular daily rhythms and sleep patterns. This was intended to mitigate potential phase shifts in circadian rhythms due to insufficient winter light exposure and to minimize the impact of individual circadian variations on the experimental outcomes [5]. Additionally, within 24 hours before the experiment, participants were required to ensure adequate sleep and abstain from alcohol or drug use.

2.3 Procedure

The experiment was scheduled between December 25, 2023, and January 2, 2024, and the room temperature was controlled at 20.5 ± 0.8°C. In order to exclude the influence of external light exposure and other activities before entering the laboratory, participants were required to rest in a dark environment for 10 minutes during the resting 1 stage before the start of the experiment [43，44]. Baseline psychological and physiological data of the individuals during the resting 1 state were collected in order to avoid the influence of individual differences on the data. Prior to the experiment, the participants were given instructions to familiarize themselves with the experimental tasks.

All participants adhered to a six-stage protocol based on typical phases in

fitness activities, with time allocations as determined Table 2. Each participant engaged in a 1-hour session. Upon the completion of each lighting environment scenario test, adjustments to the light environment scenario were followed in accordance with the specifications in Table 1. Physiological assessments were carried out throughout the entire process, with specific test items conducted the guidelines in Table 3. Questionnaires were administered both before and after the exercise phase. The experimental process, shown in Table 2, followed a structured six-stage protocol based on the typical phases of fitness activities. Each section lasted about 1 hour, and physiological tests were conducted throughout the session. Questionnaires were administered before and after the end of the exercise stage. Table 3 illustrates the test content of one experimental unit, in which the subjects were required to keep their eyes open throughout the experiment, except for the resting 1 phase.

Table 2. Experimental procedures

Time	Duration	Exercise stages	Note
8:20-8:30	10 min	Resting 1	Participants were prepared for the experiment.
8:30-8:35	5 min	Warming up	Participants adapted to the luminous environment and experienced pre-exercise state tests (Pre-test 1)
8:35-9:20	45 min	Exercising	Participants exercised in the designated luminous environment while physical data were collected (Unit 1).
9:20-9:30	10 min	Relaxing	Participants received post-exercise tests on their body conditions (Post-test 1).
9:30-10:00	30 min	Participants changed their clothes. Resting 1.	Participants exited with the next group of prepared participants.
10:00-10:05	5 min	Warming up	Participants adapted to the luminous environment and experienced pre-exercise state tests (Pre-test 2)
10:05-10:50	45 min	Exercising	Participants exercised in the designated luminous environment while physical

Time	Duration	Activity	Content
			data were collected (Unit 2).
10:50-11:00	10 min	Relaxing	Participants received post-exercise tests on their body conditions (Post-test 2)
14:20-14:30	10 min	Resting 1	Participants were prepared for the experiment.
14:30-14:35	5 min	Warming up	Participants adapted to the luminous environment and experienced pre-exercise state tests (Pre-test 3)
14:35-15:20	45 min	Exercising	Participants exercised in the designated luminous environment while physical data were collected (Unit 3).
15:20-15:30	10 min	Relaxing	Participants received post-exercise tests on their body conditions (Post-test 3)
15:30-16:00	30 min	Participants changed their clothes. Resting 1.	Participants exited with the next group of prepared participants.
16:00-16:05	5 min	Warming up	Participants adapted to the luminous environment and experienced pre-exercise state tests (Pre-test 4)
16:05-16:50	45 min	Exercising	Participants exercised in the designated luminous environment while physical data were collected (Unit 4).
16:50-17:00	10 min	Relaxing	Participants received post-exercise tests on their body conditions (Post-test 4)

Table 3. Measuring contents in each unit

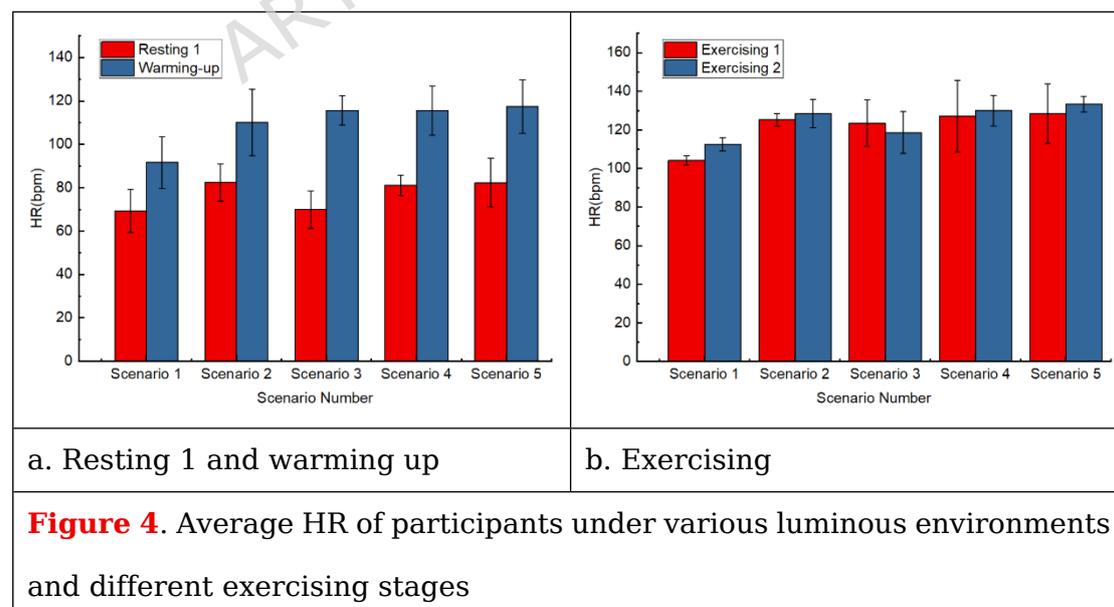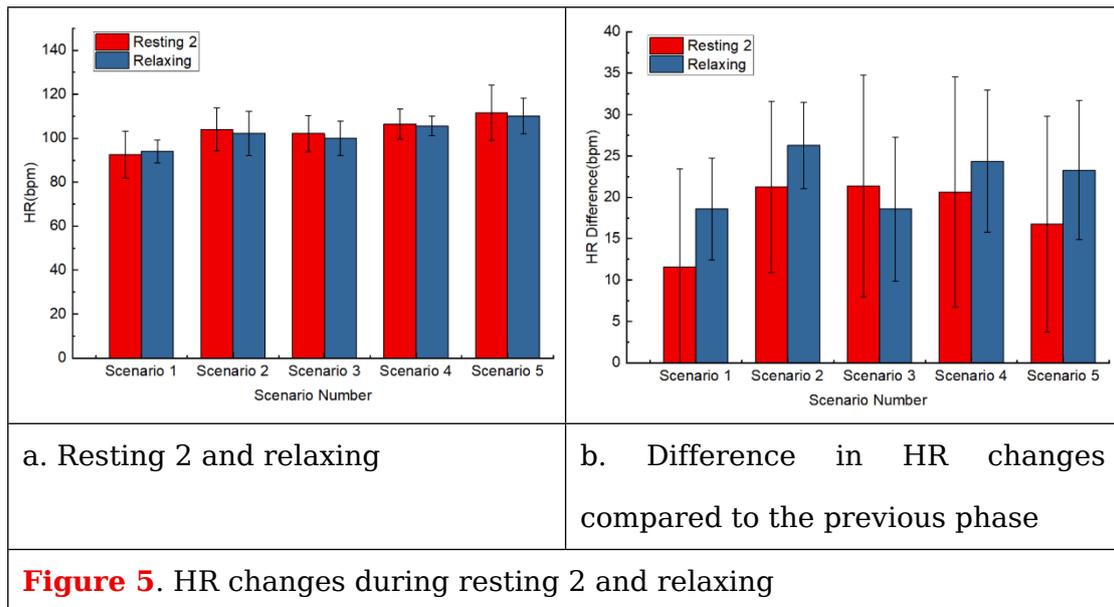| Time	Duration	Activity	Content
8:30-8:35	5 min	Warming up	EEG, ECG, SCL, PANAS, and KSS
8:35-8:55	20 min	Exercising	EGG, ECG, and SCL
8:55-9:00	5 min	Resting 2	EEG, ECG, and SCL
9:00-9:20	20 min	Exercising	EEG, ECG, and SCL
9:20-9:30	10 min	Relaxing	EEG, ECG, SCL, PANAS, and KSS

3. Results

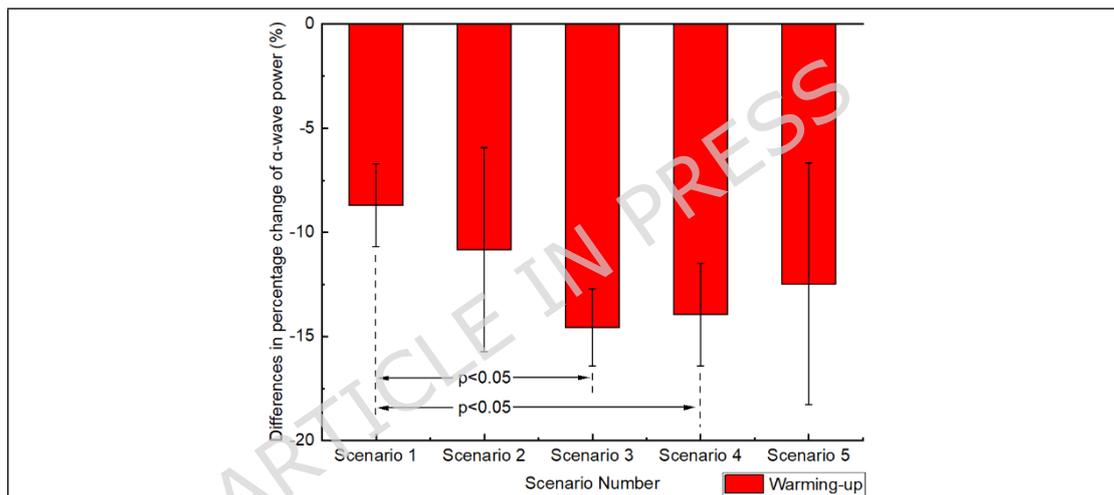### 3.1 Objective physiological parameters

(1) HR

Figure 4 shows the average HR of participants across different stages in each scenario. During the warming up phase (Figure 4a), the average HR of

participants in Scenario 1 did not achieve the intended warming up effect. In contrast, Scenarios 4 and 5 enabled participants in more effectively achieving the warming up target within the same duration, whereas Scenarios 2 and 3 performed slightly inferior. However, no statistically significant differences were observed among the scenarios ($p > 0.05$). During the exercising (Figure 4b), HR data from participants in all five scenarios indicated that the exercise intensity reached low to moderate levels (approximately 102-171 bpm). Engaging in low-to-moderate intensity fitness activities ensured relatively consistent physiological data changes among participants, thereby minimizing experimental error. During the rest and cool-down phases, as illustrated in Figure 3, participants in Scenario 1 exhibited lower heart rates (Figure 5a), whereas those in Scenario 2 showed faster heart rate recovery (Figure 5b). Participants in Scenarios 1 and 2 (200-500 lx/ 3000-5000 K) achieved better relaxation effects and faster recovery within the same time frame. No statistically significant differences were observed among the scenarios ($p > 0.05$), suggesting that lighting environments with different illuminance levels and color temperatures have some influence on participants' heart rates, but the effect is not significant.

| a. Resting 1 and warming up | b. Exercising |

Figure 4. Average HR of participants under various luminous environments and different exercising stages

a. Resting 2 and relaxing	b. Difference in HR changes compared to the previous phase

Figure 5. HR changes during resting 2 and relaxing

(2) EEG

Figure 6. Percentages of α wave power under different luminous environments during warming up

a. β wave during exercising	b. α wave during exercising
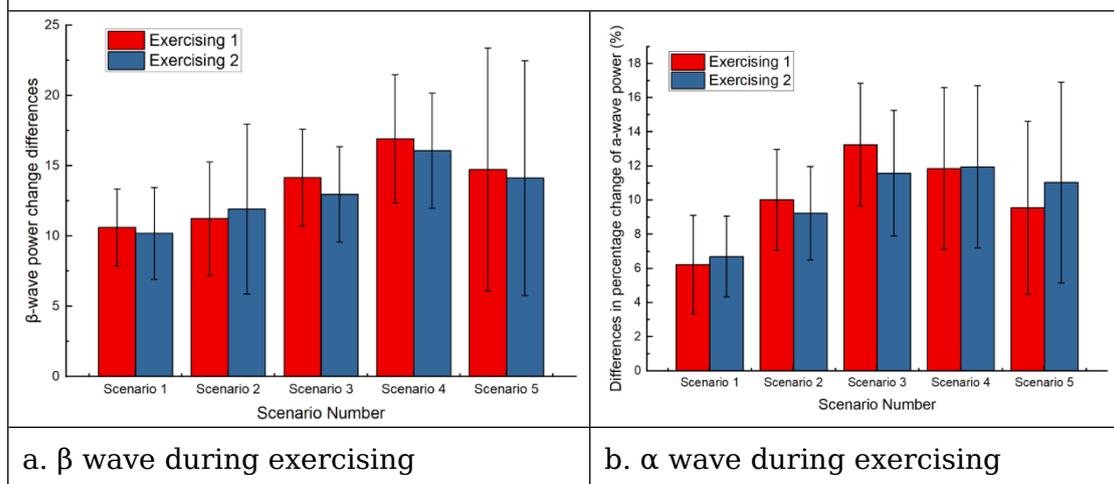
Figure 7. Changes of α, β waves under different luminous environments
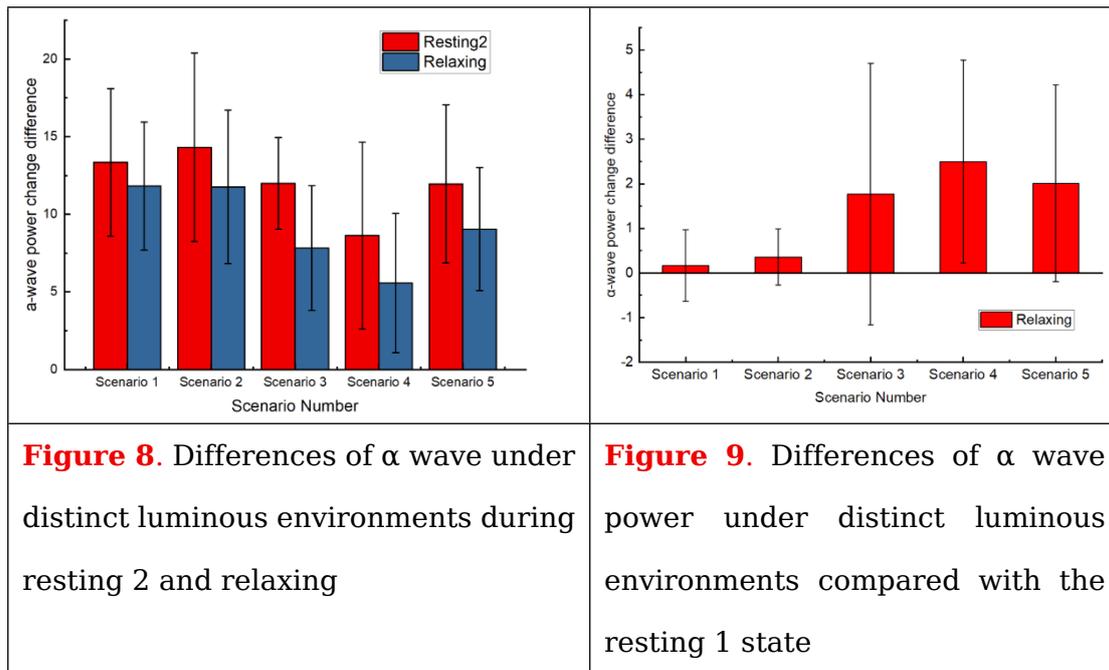
| **Figure 8**. Differences of α wave under distinct luminous environments during resting 2 and relaxing | **Figure 9**. Differences of α wave power under distinct luminous environments compared with the resting 1 state |

Independent component analysis was conducted on α-wave (8-12 Hz) and β-wave (13-30 Hz) based on the EEG data collected utilizing electroencephalographic instruments under distinct luminous environments. Figure 6 demonstrates the percentages of α-wave power during warming-up. It indicates that Scenarios 3, 4, and 5, followed by Scenario 2, showed an obvious reduction of α-wave power. In contrast, Scenario 1 exhibited a lower decrease in the α-wave power. This indicated that the individuals in Scenarios 3, 4, and 5 (800-1000 lx/5000-6500 K) showed enhanced EEG activity and a higher arousal level, resulting in a more effective warming up. During exercising, the changes in β wave power (Figure 7a) suggest a more significant increase in Scenarios 3, 4, and 5, while Scenario 2 showed a moderate increase, and Scenario 1 exhibited the smallest change. Notably, a significant difference was observed ($p < 0.05$) between Scenarios 1 and 4 and between Scenarios 2 and 4. Meanwhile, α-wave power percentage changes in different light environments (Figure 7b). The decrease in α-wave power percentage was more significant in Scenarios 3 and 4, followed by Scenarios 2 and 5, while Scenario 1 exhibited the smallest reduction. Statistically significant differences were identified between Scenarios 1 and 3 and between Scenarios 1 and 4 ($p < 0.05$). It confirms a higher EEG activity and arousal degree in

Scenarios 3, 4, and 5 (800-1000 lx/5000-6500 K), resulting in improved cognitive performance and faster response speed. It aligns with the findings in the previous literature [45-47]. During resting 2 and relaxing, Figure 8 shows the differences between resting 2 or relaxing and the previous exercising stage in each scenario. Scenarios 1 and 2 showed a higher increase in the α-wave power, while Scenarios 3, 4, and 5 showed a lower increase. A significant difference was observed between Scenarios 1 and 4 and Scenarios 2 and 4 ($p < 0.05$). In Figure 9, the α-wave in the relaxation phase of Scenarios 1 and 2 showed a relatively small difference compared with resting 1, indicating that participants had basically returned to a calm state, while the gap between the α-wave and the resting 1 phase is larger in Scenarios 3, 4, and 5. A significant difference was observed ($p < 0.05$) between Scenarios 1 and 4, and 2 and 4. These results suggested that the individuals in low illuminance and low color temperature light environments (Scenarios 1 and 2; 200-500 lx/3000-5000 K) recovered faster.

(3) SCL

Figure 10 exhibits the differences between the exercising 2, relaxing stages, and resting 1 stages on SCL. The difference in SCL change was observed between the exercise 2 and post-exercise relaxation phases compared to the resting phase. A significant difference was observed between Scenarios 1 and 4 ($p < 0.05$). In Scenarios 1 and 2, participants exhibited greater SCL fluctuations, while Scenarios 3, 4, and 5 showed relatively small variations. SCL fluctuations are associated with human fatigue states and emotional expression [48]. These findings indicated that a delayed onset of fatigue, higher endurance, and more positive emotional responses can facilitate the maintenance of good athletic condition. During relaxation, Scenarios 4 and 5 demonstrated a more pronounced reduction in SCL, likely due to the relatively small increase in SCL during the exercising phase. Meanwhile, Scenarios 1, 2, and 3 showed a lesser reduction in SCL.
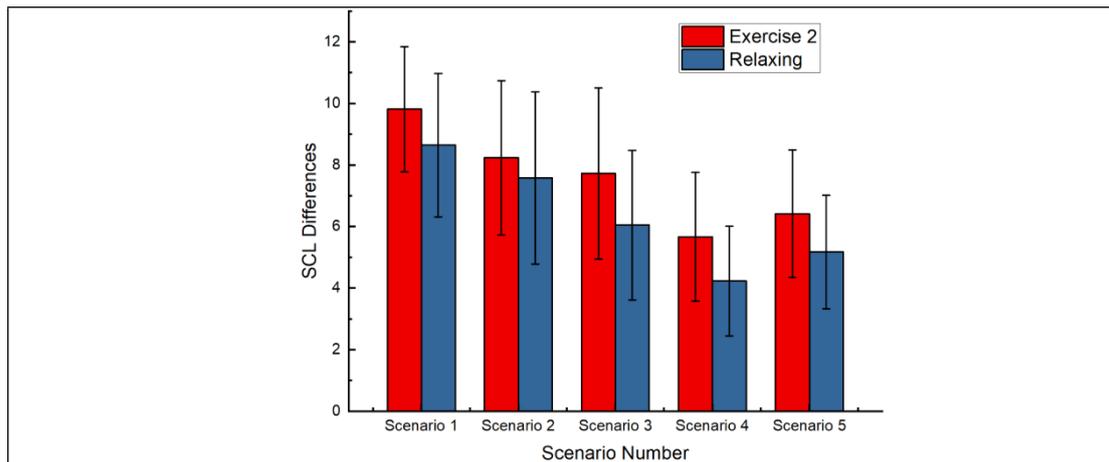
Figure 10. Differences in SCL across various stages in different scenarios

### 3.2 Subjective questionnaire analysis

(1) Subjective emotions: In this study, the positive and negative psychological feelings of individuals were assessed by calculating the difference between their positive and negative scores, as illustrated in Figure 11a. No significant differences were observed in pre-test scores among different scenarios ($p > 0.05$). The individuals showed the most positive emotions in Scenario 4, followed by 2, 3, and 5, while Scenario 1 showed the most negative emotions. Figure 11b demonstrated a significant difference between some scenarios in the post-test results ($p < 0.05$). Participants exhibited the most positive emotions in Scenario 4, followed by a relatively comparable level of Scenarios 3 and 5, Scenario 2, and Scenario 1, with the most negative emotions.

a. Pre-test

b. Post-test
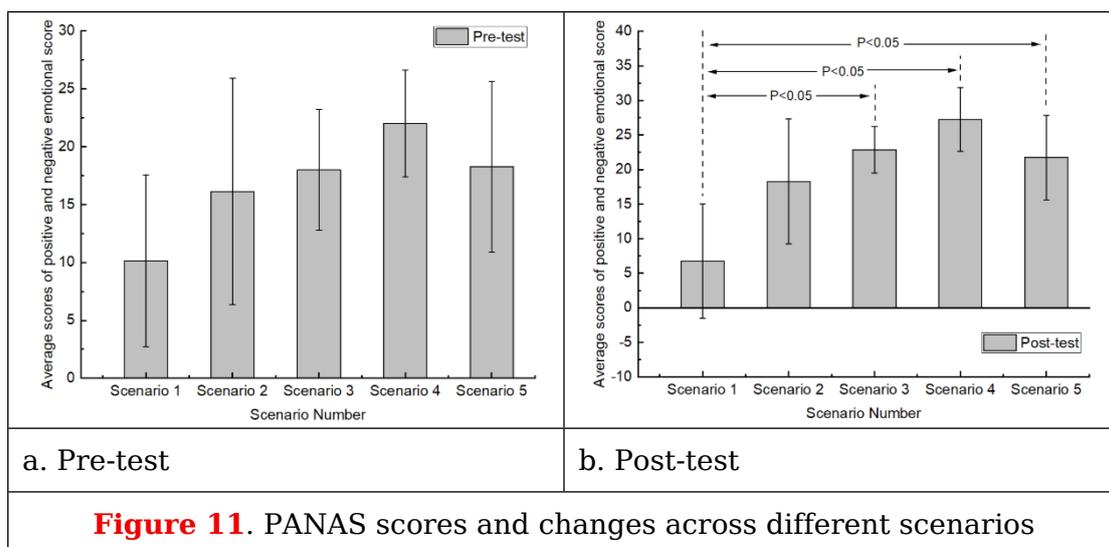
Figure 11. PANAS scores and changes across different scenarios

(2) Alertness: The influence of different luminous environments on alertness

in this study was evaluated using data obtained through the KSS scale, as shown in Figure 12. Pre-test results indicated that participants exhibited similar levels of sleepiness across all scenarios, with no significant differences (p > 0.05). As illustrated in Figure 12b, the post-test showed that Scenario 1 obtained an average value exceeding 6, demonstrating that participants were relatively sleepy. Conversely, Scenarios 3, 4, and 5 exhibited a higher alertness, and Scenario 2 exhibited a medium level of alertness. The differences between the pre- and post-test were relatively stable, with a remarkable influence of the luminous environment on alertness and the significant difference among scenarios (p < 0.05).

a. Pre-test

b. Post-test
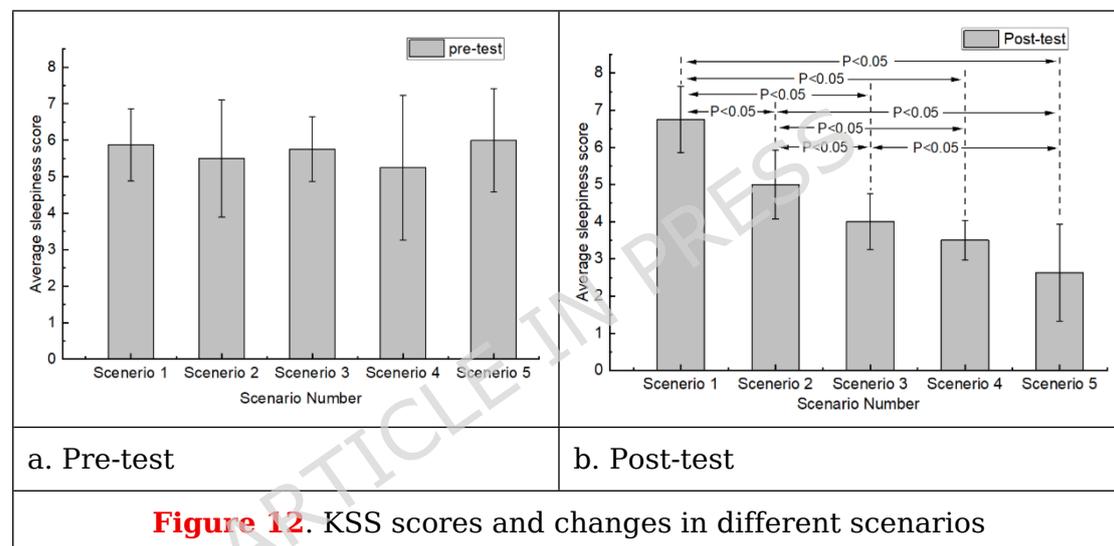
Figure 12. KSS scores and changes in different scenarios

4. Discussion

This study measured various physiological and psychological parameters under different luminous environments, confirming that the variations in luminous environments show correlations with physiological states and psychological responses during warming up, exercising, and relaxing.

Warming up: In Scenario 1 (200 lx/3000 K), the average HR of most participants remained below 90 bpm. However, when the illuminance exceeded 500 lx and a color temperature surpassed 5000 K, HR of nearly all participants exceeded 90 bpm across all experimental scenarios at a comparable warming-up intensity. Additionally, EEG data revealed that after warming up, the percentage of α wave power endured a lower reduction in

Scenario 1 (200 lx/3000 K), indicating insufficient alertness and a poor arousal degree. In contrast, Scenario 2 demonstrated a better arousal degree, while Scenarios 3, 4, and 5 showed even higher arousal levels. This suggests that an appropriate high illuminance and high color temperature can enhance emotional arousal and concentration, thus benefiting warming-up efficiency, which is consistent with the results obtained by the previous studies [49-51]. Effective warming up can activate neural hubs and improve blood circulation, thus enhancing concentration and mitigating anxiety. Short-duration, low-intensity warming-ups can both prevent muscle fatigue and increase exercise performance [52]. Considering the heart rate and EEG data, Scenario 2 (500 lx/5000 K) can satisfy the basic light environment needs in the warming-up phase, while Scenarios 3, 4, and 5 (800 lx-1000 lx, 5000 k-6500 k) can be selected according to the individual preference as the luminous environment for the optimal warming-up exercise.

Exercising: During exercise, individuals must maintain a certain exercise intensity for a prolonged period to achieve the health-improving goal. HR is usually utilized to evaluate the intensity of exercising [53]. This study maintained HR at approximately 102-170 bpm across all lighting conditions, which falls within the low-to-moderate exercise intensity range as defined by ACSM's HR target guidelines for different exercise intensities. In Scenario 1 (200 lx/3000 K), participants exhibited the lowest HR, while individuals within a partial age range showed an HR of low-intensity exercise after the process, suggesting a poor exercising outcome. SCL data showed the following ranking: Scenario 1>2>3>5>4, with the peak value observed in Scenario 1 (200 lx/3000 K), where individuals report feeling exhausted after exercising. This exhaustion cannot be effectively mitigated under a low-illuminance, low-color temperature luminous environment. Meanwhile, Scenario 4 obtained the lowest SCL, with the fatigue of individuals being effectively alleviated. Therefore, a favorable exercise state can be maintained. EEG data revealed that in Scenarios 3 (800 lx/5000 K), 4 (800 lx/6500 K), and 5 (1000 lx/6500 K),

the percentage of α wave power decreased, while the β wave power value increased and remained at a high level. These results demonstrate that participants exhibited a state of alertness, accompanied by heightened brain activity and enhanced mental agility. In comparison, Scenario 2 (500 lx/5000 K) is relatively worse, while Scenario 1 (200 lx/3000 K) exhibited the lowest alertness. The KSS scale revealed a positive correlation between illuminance, CCT, and alertness. The order of positive emotion is Scenario 4 > 3 >5 > 2 >1. PANAS suggested that participants in Scenario 4 (800 lx/6500 K) had the most positive emotions, while in Scenario 2, the emotions of the participants were the most stable. In Scenario 1, the positive emotions of the participants decreased after exercising. Combining physiological and psychological data, Scenario 2 (500 lx/5000 K) can meet the basic luminous environment demands of the exercise phase, while Scenarios 3, 4, and 5 (800-1000 lx, 5000-6500 k) can be used as the optimal range of luminous environment in the exercise phase.

Resting 2 and Relaxing: In Figures 5a and 5b, the HR of the participants showed a faster recovery speed in Scenario 2, indicating a good recovery after exercising, while Scenario 1 exhibited the lowest HR during relaxing and resting 2. Therefore, a luminous environment with low illuminance and low color temperature can better facilitate resting 2 and relaxing after exercising. In Scenarios 3, 4, and 5, participants showed a higher HR with a relatively poor recovery, which cannot meet the resting 2 demand of the participants. The EEG data show that in Scenarios 1 and 2, the individuals' α waves have recovered significantly. Compared with the resting 1 state, the individual's EEG α wave in Scenarios 1 and 2 had largely returned to baseline levels, indicating effective recovery, while the α wave power values of the participants in Scenarios 4 and 5 exhibited a lower recovery efficiency following an equal duration of rest and relaxation interval. Scenarios 1 and 2 (200-500 lx/3000-5000 K) can effectively support rest and relaxation. According to the lighting recommendation value of the International Sports

Federation and the lighting design standard of Chinese buildings, the horizontal illuminance of non-competitive badminton fitness sports should exceed 300 lx, and the color temperature should not be lower than 4000 K, so the illuminance of the relaxation phase should be controlled at 300-500 lx, color temperature should be controlled in 4000-5000K.

5. Conclusion

(1) The luminous environment parameters of the indoor exercising facilities have an impact on both the physiological indicators, including HR, SCL, and EEG, and the psychological index, such as emotions and alertness. The parameters should be set based on the illuminance measured near the eyes.

(2) The luminous environment parameter setting of indoor exercising facilities should cater to the need for three different exercising stages: warming up, exercising, and relaxing. The findings of this study suggested that warming up and exercising have a higher demand on luminous environment parameters, which require 800-1000 lx illuminance, 5000-6500 K color temperature, and 309.25-387.25 lx, 5096.00-6423.25 K color temperature near the eyes. To meet the basic needs of the light environment in the exercising process, the illuminance should be set to about 500 lx, while the color temperature should be approximately 4000-5000 K. Under these circumstances, the illuminance at the near-eye is about 200.50 lx, and the color temperature is about 5060 K. The demand for the light environment parameters during the stage of resting 2 and relaxing is relatively low, and it is necessary to maintain a stable state for the participants. Therefore, the light environment parameters of Scenario 2 are more reasonable. However, some parameters in Scenario 1 can also help the participants transform into a relaxed state. Drawn from the lighting requirements of the restroom in the architectural lighting design standard, the illuminance should be set as 300-500 lx, the color temperature as 4000-5000K, and the illuminance at the near-eye area should be set as 144.32 lx-200.50 lx, while the color temperature should be set as 4050-5060 K.

(3) This study has the following limitations: First, the experiment focused

solely on badminton, while other sports may involve different physiological and psychological demands, leading to varying lighting requirements. Second, the dimensions of the experimental venue differed from those of real-world sports settings, which could also influence participants' physiological and psychological responses. Third, the laboratory lighting environment was not identical to that of actual sports venues—for instance, natural light was not considered, and the impact of surface reflectivity on indoor lighting conditions was overlooked. To minimize the effects of lighting discrepancies, the study also measured the lighting parameters near participants' eyes. Additionally, since exergaming differs from real sports, participants' performance in the experimental setting might not fully align with that in actual sports. To reduce such discrepancies and ensure the realism of the exercise simulation, the study required participants to increase their range of motion to elevate their heart rate, ensuring it reached low-to-moderate exercise intensity levels, thereby more accurately simulating real-world sports conditions. Finally, the study did not account for neural complexity. EEG responses to light are highly individualized and can be influenced by factors beyond the experimental manipulations. These aspects should be considered in future research.

Data availability：

The authors confirm that the data supporting the findings of this manuscript are available within the article and its ESI.

Author Contributions:

Xuan Li: methodology, software, investigation, data curation, writing-original draft preparation, writing-review and editing, project administration; **Weifeng Zhao**: validation, writing-review and editing; **Xiaowei Bai**: investigation, resources. All authors have read and agreed to the published version of the manuscript.

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