Research on the Optimization of Illuminance and Color Temperature in College Table Tennis Courts Based on Non-visual Effects and Sports Performance

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ABSTRACT To investigate the influence of electromagnetic radiation characteristics in indoor lighting environments on athletes' physiological responses and sports performance, this study proposes a comprehensive optimization framework for illuminance and correlated color temperature (CCT) in university table tennis courts based on non-visual photobiological effects and athletic performance. A two-dimensional evaluation system integrating subjective perception, reaction speed, and technical performance was established under twelve lighting conditions generated by four CCT levels (3500 K , 4500 K, 5500 K, and 6500 K) and three illuminance levels (300 lx, 500 lx, and 700 lx). The CRITIC objective weighting method and quadratic response surface regression were employed to construct a multi-objective optimization model for intelligent lighting parameter design. Experimental results indicate that the optimal athletic performance is achieved under 6500 K with 500–700 lx, whereas the optimal non-visual physiological state favors 5500 K with 500–700 lx. By integrating both objectives, the proposed model identifies an optimal operating point of 700 lx and 5800 K, providing a balanced solution for performance enhancement and human-centric lighting. The proposed optimization strategy offers an engineering-oriented methodology for adaptive spectral regulation, electromagnetic radiation field optimization, and intelligent LED illumination design, with potential applications in sports facilities and advanced indoor lighting systems.

INDEX TERMS electromagnetic radiation characteristics, intelligent LED lighting, non-visual photobiological effects, correlated color temperature, illuminance optimization

I. INTRODUCTION

WITH the popularization of health concepts and the development of sports, the construction of sports build ings has continued to advance, and the light environment has become a core evaluation indicator for indoor sports venues. University table tennis courts are used frequently and serve a concentrated user group, and the quality of their light environment is directly related to sports safety and users' health. However, existing design still mainly focuses on traditional visual indicators. University table tennis courts mainly serve young students and are primarily used for amateur exercise. They are characterized by long light exposure duration and greater sensitivity to visual comfort and non-visual health, and they differ significantly from professional venues and public sports spaces in terms of usage needs and behavioral patterns. Therefore, targeted research is urgently needed. The two core pathways through which light exerts its effects on the human body are illustrated in Figure 1.

Since the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs), research on the non-visual pathways of light has gradually deepened. Studies have confirmed that light can regulate human physiological functions through non-visual pathways sensitive to short-wave blue light (460–480 nm). Existing studies have further clarified that key parameters of the light environment, especially color temperature and illuminance, are significantly associated with non-visual human states such as alertness, cognitive performance, mood, and fatigue [1-3]. A large number of studies have also taken color temperature and illuminance as core variables and confirmed that both are highly correlated with non-visual indicators [4-6]. In addition, studies targeting young groups have further verified

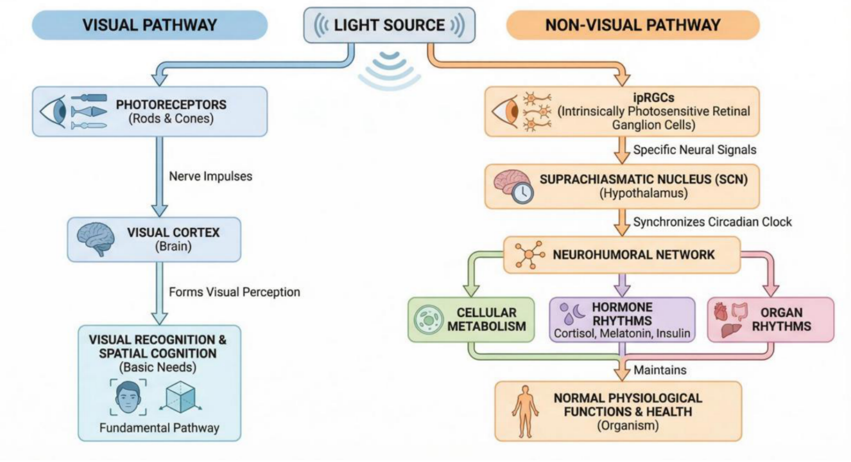

FIGURE 1. shows the two core pathways of the effect of light on the human body

the mechanisms of non-visual photobiological effects. M.I. Silvani et al. [7] showed that increasing the proportion of short-wave blue light in a light source or adopting high color temperature lighting can strengthen non-visual photobiological effects and thereby enhance human alertness. Burattini et al. [8] experimentally confirmed that exposure to cool white LED light (6800K) can maintain human alertness and suppress its natural decline over task duration, highlighting the important regulatory role of non-visual light effects on cognitive performance. At present, research related to the non-visual effects of the light environment has already been applied in office and teaching environments [9-10].

In the field of sports, multiple studies have confirmed that the non-visual effects of the light environment have a significant impact on sports performance, and the conclusions of these studies provide important references for sports lighting design. Wen et al. [11] experimentally confirmed that high color temperature lighting can significantly affect swimmers' athletic performance and suggested incorporating the non-visual effects of light into sports lighting design considerations. The experiment by Leichtfrie et al. [12] showed that morning bright light exposure can improve the cognitive performance of shooting athletes, but has no significant effect on shooting scores. For small-ball sports such as table tennis and badminton, Li Xian et al., using university students as the research subjects, found that light environment parameters such as color temperature and illuminance significantly affect the reaction time and target recognition efficiency of table tennis and badminton participants. Meanwhile, the experimental studies by Tulppo and Beaven et al. [13-14] both found that light environments with a high proportion of blue light are beneficial for improving athletes' sports performance.

Based on this, the present study focuses on the core problem in the lighting design of university table tennis courts, namely the failure to simultaneously account for non-visual effects and sports performance. The core research content is to clarify the relationship between non-visual state and sports performance, identify the preferred combination of lighting parameters suitable for university table tennis, construct a comprehensive optimization objective and recommended lighting parameter standards that take both into account, and ultimately provide a scientific basis for the evaluation and design optimization of lighting environment quality in university table tennis courts.

II. MATERIALS AND METHODS

A. EXPERIMENTAL SCHEME

In order to avoid the influence of the external light environment on the experiment as much as possible, this study selected a room with a relatively regular internal structure (6.8 m $\times$ 4.2 m $\times$ 3.5 m) at Hebei University of Engineering, as shown in Figure 1, and constructed a darkroom. All windows around the darkroom were covered with full blackout film, and the surrounding walls were covered with black curtains. The laboratory was equipped with an intelligent adjustable LED lighting system, as shown in Figure 2 (color temperature adjustment range: 2700K–6500K; illuminance adjustment range: 0–1000lx; color rendering index Ra $\geq$ 90). The luminaires were evenly installed directly above the site. At the same time, a standard table tennis table (1.525 m $\times$ 2.740 m), a ball-serving machine (model: Pangbote NOVA), and sports protective equipment were provided for the subjects. To ensure that the experimental scenario matched the real conditions of table tennis as closely as possible, the ambient temperature and humidity were regulated to a range suitable for exercise to improve the simulation conditions [15-17]. Meanwhile, before each experiment began, light environment parameters were measured to ensure that the parameters were basically consistent.

1) Lighting Parameter Settings

Given that non-visual indicators such as CS and EML have not yet been incorporated into sports lighting engineering standards, while illuminance and color temperature, as common parameters, can effectively characterize non-visual stimulus features, this study selected these two variables

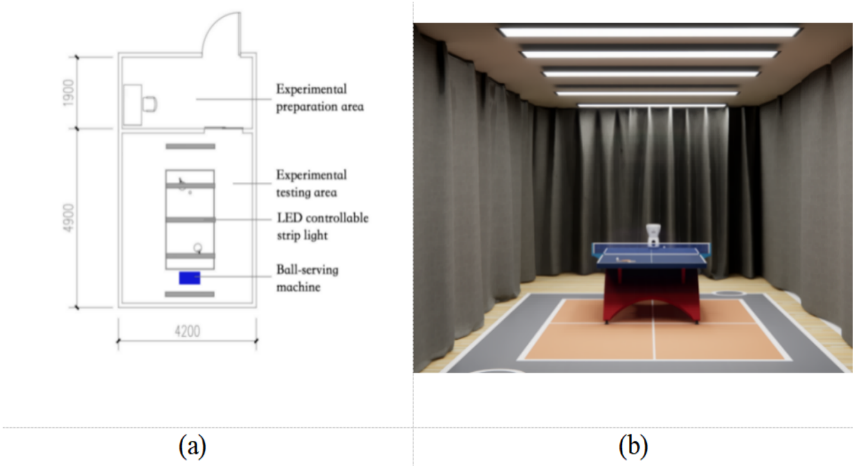

FIGURE 2. Schematic diagram of laboratory layout: (a) Laboratory Layout plan; (b) Schematic diagram of the laboratory layout.

as independent variables and quantified the performance of non-visual effects through subjective and objective indicators. The parameter settings were determined with reference to the lighting parameter specifications clearly stated in the Standards for Lighting Design and Testing of Sports Venues, as well as relevant research conclusions regarding the effects of lighting parameters on human non-visual effects [18-19]. Three illuminance levels (300lx, 500lx, 700lx) and four-color temperatures (3500K, 4500K, 5500K, 6500K) were selected and combined into 12 different light environments. The specific light environment settings are shown in Table 1.

B. PARTICIPANTS

Before the formal experiment, the required sample size was estimated using G*Power software to be no fewer than 24 participants. Ultimately, 30 graduate student volunteers from universities were recruited, with an average age of 24.27 $\pm$ 1.325 years (15 males and 15 females), all of whom had basic table tennis experience. None of the subjects had emotional disorders or chronic diseases, all had normal corrected vision, and all were right-handed. One week before the experiment, the subjects were required to maintain a regular schedule, avoid trans-time-zone travel within the prior three months, and avoid long-term exposure to special light environments. On the day before the experiment, they were required to ensure 8 hours of sleep and refrain from consuming coffee, strong tea, and similar beverages. This study was approved by the Ethics Committee of Hebei University of Engineering, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

C. MEASUREMENT INDICATORS

1) Sports Performance Evaluation Indicators

This study selected the technical standard-reaching dimensions identified in existing research as the evaluation content for sports performance in the table tennis event among ordinary university students. This dimension includes five indicators: forehand attack, backhand block, backhand long push, left push-right attack, and block-side-step smash. Different weights were assigned to each indicator according to gender, as shown in Table 2. A weighted calculation was then used to obtain a comprehensive technical standard-reaching score, which was used to reflect the sports performance level of the subjects. During the experiment, the serving machine maintained consistent parameters for all subjects under the same technical indicator.

2) Non-Visual Evaluation Indicators

Considering the usage scenario of sports venues, this experiment selected average reaction time, mood, fatigue, and alertness as the non-visual evaluation indicators. As a physiological indicator of the non-visual regulation of light, alertness has been shown in studies to be improved by high color temperature light and blue light, possibly through melatonin suppression and activation of the ipRGC pathway, which is well suited to the need for athletes in sports venues to remain awake and alert. Reaction time can serve as an objective reference indicator of cognitive function, and tasks such as the PVT can capture the influence of light on attention and information processing speed. Mood is a key psychological dimension that characterizes the influence of athletes' emotional state on sports experience and performance. Fatigue reflects the cumulative effect of light on athletes' physical and mental load. These four indicators cover the three major dimensions of physiology, cognition, and psychology, and corresponding assessment tools and some supporting studies are available, making them suitable as evaluation indicators of the non-visual effects of light in sports venue scenarios.

(1) Average Reaction Time The Psychomotor Vigilance Task (PVT) is used to evaluate objective alertness [20]. In this experiment, during each lighting condition test procedure, one 3-minute PVT task was synchronously arranged. Among the multi-dimensional indicator system of the PVT task, this study selected average reaction time as the core evaluation indicator. The smaller the value, the better the

TABLE 1. Light Environment Setting Conditions

Condition	Illuminance–Color Temperature	Condition	Illuminance–Color Temperature	Condition	Illuminance–Color Temperature
A1B1	300lx–3500K	A2B1	500lx–3500K	A3B1	700lx–3500K
A1B2	300lx–4500K	A2B2	500lx–4500K	A3B2	700lx–4500K
A1B3	300lx–5500K	A2B3	500lx–5500K	A3B3	700lx–5500K
A1B4	300lx–6500K	A2B4	500lx–6500K	A3B4	700lx–6500K

TABLE 2. The weight of sports performance evaluation indicators

Indicator Name	Weight of Grade Evaluation Indicator (Male)	Weight of Grade Evaluation Indicator (Female)
Forehand attack	25.53%	18.00%
Backhand block	19.15%	16.00%
Backhand long push	19.15%	24.00%
Left push-right attack	14.89%	26.00%
Block-side-step smash	21.28%	16.00%

alertness response performance.

(2) Subjective Mood Subjective mood was evaluated using the Chinese revised short-form scale of the Profile of Mood States (POMS) by Zhu Beili [21], which is suitable for emotion- and sport-related research among Chinese subjects. The scale includes descriptive words for positive emotions and descriptive words for negative emotions. Each descriptive word has five levels corresponding to scores from 0 to 4, and a higher score indicates a stronger emotion. The Total Mood Disturbance (TMD) score was calculated to characterize overall emotional state, and a higher total mood disturbance value indicates a higher level of negative emotion.

(3) Subjective Fatigue Fatigue includes mental fatigue and physical fatigue. The relevant questionnaire items for mental fatigue include: “I feel very fatigued,” “I feel very weak,” and “I feel energetic.” The questions for physical fatigue include: “I feel a headache” and “My eyes feel dry.” For all questions, the subjects were required to select the accuracy of each statement according to their own feelings. A 7-point scale was used for evaluation, and the total fatigue score of each subject was calculated as the analytical data. A higher score indicates more severe fatigue.

(4) Subjective Alertness Subjective alertness was assessed using the Karolinska Sleepiness Scale (KSS) [22]. Alertness was divided into 10 stages, ranging from 1 to 10, from extremely alert to extremely sleepy and unable to remain awake. During the experiment, subjects were required to choose according to their current state of sleepiness. A higher score indicates a higher degree of current sleepiness and lower alertness.

D. PROTOCOL

This study adopted a within-subject design, and all subjects were required to complete tests under all 12 lighting conditions. To control for order effects and fatigue effects, the test sequence was balanced and randomized using a Latin square design, ensuring random crossover of condition presentation order among different subjects. In addition, all subjects followed a unified standardized experimental procedure as shown in Figure 3. Each subject was required to complete the tests for the lighting combinations in sequence. The interval between tests under different lighting combinations was set at 10 minutes (washout period), during which the subjects remained in a natural lighting environment without artificial lighting intervention and could engage in light relaxation activities (such as sitting quietly or slow walking), so as to quickly eliminate the influence of the previous lighting condition while relieving test fatigue. To ensure data validity, participants’ baseline mood and fatigue levels were assessed before the start of each new condition to confirm they had returned to comparable levels. Additionally, a statistical check for carryover effects was performed, confirming that the randomized Latin square design effectively balanced the influence of cumulative fatigue across the 12 testing sessions.

1) Warm-up Preparation Stage

The subjects first completed a standardized warm-up procedure, including shoulder activities, core stability training, hip joint flexibility exercises, and sports psychological adjustment. Throughout the process, they were exposed to a natural lighting environment without artificial lighting intervention. The warm-up duration was strictly controlled at 10 minutes to ensure consistency in the exercise state of all subjects.

2) Lighting Calibration and Light Adaptation Stage

After each round of lighting switching, the light environment parameters in the test area were first measured to ensure that the deviation between the average illuminance and the set value was $\leq \pm 20$ lx, the color temperature deviation was $\leq \pm 50$ K, and the illuminance uniformity was ≥ 0.8. After the lighting equipment operated stably according to the experimental design parameters, the subjects were guided into the experimental site for 3 minutes of light adaptation (based on the physiological response

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mechanism of non-visual effects, 1–2 minutes can activate retinal photosensitive ganglion cells, and 3 minutes can bring non-visual effects into a stable state, thereby ensuring the consistency of the test results).

3) Test Implementation Stage

After light adaptation, a series of tests were completed in sequence: subjective mood assessment, fatigue assessment, alertness test, and table tennis-specific sports performance test. During the 12 lighting combination tests, one 15-minute centralized rest period was arranged midway (for example, after completing 6 rounds), during which drinking water and a quiet resting environment were provided to relieve accumulated fatigue.

III. RESULTS

This study takes "optimization of non-visual indicators" and "optimization of athletic performance" as its dual core objectives. First, based on measures of emotion, alertness, fatigue, and reaction time, the non-visual state index I was established using the CRITIC weighting method [23], while athletic performance was represented by the technical compliance rate. Two-way repeated-measures analysis of variance (ANOVA) was performed to investigate the effects of illuminance, correlated color temperature (CCT), and their interaction. Significant effects were further analyzed to identify the optimal lighting combinations. After standardizing the two types of indicators, the CRITIC method was applied again to determine comprehensive weights, and a comprehensive objective function was constructed. Combined with quadratic response surface regression, the optimal lighting parameters balancing athletic performance and non-visual effects were derived as 700 lx and 5800 K. The quadratic response surface regression model yielded an R^2 of 0.735, indicating that while the model captures the primary trends of the lighting parameters, approximately 26.5% of the variance remains unexplained. This residual variance may be attributed to individual differences in circadian rhythm, baseline fatigue levels of participants, or unmeasured environmental factors such as psychological expectations. Furthermore, as the predicted optimal CCT of 5800 K is located towards the upper end of our experimental range (3500–6500 K), the potential for even higher color temperatures (e.g., >6500 K) to further enhance non-visual alertness and athletic performance cannot be ruled out. Future studies should consider broadening the color temperature spectrum to identify the definitive saturation point of these effects.

Data processing and statistical analyses were conducted using IBM SPSS 24 and Python. Raw data were initially screened to exclude missing, erroneous, and outlier values, followed by necessary corrections. Reliability analysis revealed that the Cronbach's α coefficients for all subjective evaluation scales exceeded 0.7, confirming the reliability of the measurements. Normality tests verified that both the non-visual state index I and technical compliance rate followed a normal distribution ($p > 0.05$). Mauchly's test of sphericity indicated that the Greenhouse–Geisser correction was required for the CCT dimension, whereas sphericity assumptions were satisfied for other dimensions ($p > 0.05$). Accordingly, subsequent repeated-measures ANOVA, pairwise comparisons, and simple-effects analyses were performed.

A. CONSTRUCTION OF THE NON-VISUAL STATE INDEX I

The non-visual state index I constructed in this study consists of four inverse indicators: emotion, alertness, fatigue, and reaction time. Since all four indicators are inverse measures where higher scores represent poorer physiological and psychological states, reverse processing and dimensionless standardization were first performed. The weights of each indicator were then determined using the CRITIC method, with the calculation results presented in Table 3. Emotion and alertness exhibited the highest weights, at 0.3726 and 0.2297, respectively. In contrast, fatigue had the lowest weight, at only 0.1902.

TABLE 3. Weights of Standardized Evaluation Values for Lighting Environments

Indicator	Standard Deviation	Conflict	Information Content	Weight
Mood	0.2041	3.1629	0.6456	0.3726
Alertness	0.2051	1.9402	0.3980	0.2297
Fatigue	0.1721	1.9155	0.3296	0.1902
Reaction Time	0.1840	1.9533	0.3594	0.2074

After reverse processing of the non-visual indicators and calculation of the weights, an indicator dataset Z = (Z1, Z2, ..., Zn) and the corresponding weights of each indicator W = (W1, W2, ..., Wn) can be obtained. The calculation formula for the non-visual state index I is shown in Equation (1).

$$I = \sum_{i=1}^{n} W_i Z_i \tag{1}$$

Where, $0 \leq W_i \leq 1$ and it satisfies $\sum_{i=1}^{n} w = 1$. The non-visual state index I was calculated for each of the 12 lighting conditions. The results, summarized in Table 4, provide the empirical basis for subsequent optimization and verification of the CRITIC weighting method. As shown in Table 4, the index I exhibits a clear trend with changes in CCT and illuminance, with the highest mean values (indicating better non-visual states after reverse processing) concentrated around the 5500 K and 6500 K conditions.

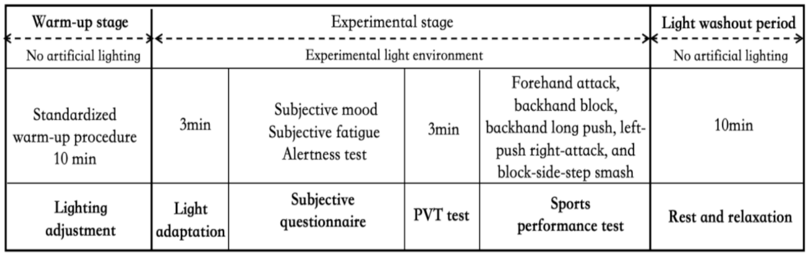


FIGURE 3. Experimental flowchart

TABLE 4. Mean values and standard deviations of the non-visual state index I under 12 lighting conditions

Illuminance (lx)	CCT (K)	Non-visual State Index I (Mean ± SD)
300	3500	0.412 ± 0.054
300	4500	0.458 ± 0.048
300	5500	0.512 ± 0.062
300	6500	0.495 ± 0.051
500	3500	0.445 ± 0.057
500	4500	0.502 ± 0.043
500	5500	0.587 ± 0.055
500	6500	0.564 ± 0.059
700	3500	0.482 ± 0.061
700	4500	0.534 ± 0.052
700	5500	0.625 ± 0.049
700	6500	0.608 ± 0.053

B. EFFECTS OF ILLUMINANCE AND COLOR TEMPERATURE ON TECHNICAL COMPLIANCE AND IDENTIFICATION OF THE PREFERRED THRESHOLD FOR SPORTS PERFORMANCE

The repeated-measures analysis of variance results for technical compliance showed that the main effect of illuminance was significant ($F = 20.609$, $p < 0.001$), the main effect of color temperature was significant ($F = 19.124$, $p < 0.001$), and the interaction effect between illuminance and color temperature was also significant ($F = 2.870$, $p = 0.011$). This indicates that the threshold for technical compliance needs to be judged in combination with specific condition combinations. As shown in the heat map on the left side of Figure 4, the high-value area of technical compliance was concentrated at 6500K, and the peak appeared at 700lx. The marginal trend plot on the right further shows that as illuminance increased from 300 lx to 500 lx and 700 lx, the mean values at each color temperature generally shifted upward, with 6500 K always remaining at the top. This indicates that the optimal threshold for technical performance tends to favor high color temperature and medium-to-high illuminance.

The descriptive statistics of technical compliance are shown in Table 5. In terms of combination means, the highest-ranked combination for technical compliance was 700lx + 6500K (76.003 ± 4.676), followed by 500lx + 6500K (75.390 ± 5.769) and 700lx + 5500K (73.473 ± 5.538). Using "no significant difference from the optimal combination" as the criterion for the preferred interval, the results showed that 500lx + 6500K ($p = 0.378$), which was not significantly different from 700lx + 6500K, was included in the optimal combination set. Further examination showed that, in the dimension of sports performance, the preferred illuminance and color temperature ranges were significantly biased toward high color temperature and medium-to-high illuminance conditions.

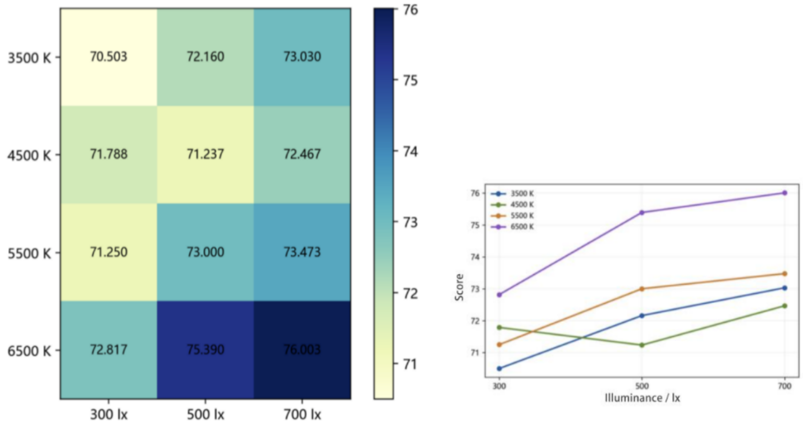
TABLE 5. Descriptive statistics of technical compliance under 12 lighting conditions

Illuminance (lx)	Color Temperature (K)	Mean ± Standard Deviation
300	3500	70.503 ± 5.045
300	4500	71.788 ± 4.790
300	5500	71.250 ± 4.740
300	6500	72.817 ± 5.449
500	3500	72.160 ± 4.689
500	4500	71.237 ± 5.457
500	5500	73.000 ± 5.365
500	6500	75.390 ± 5.769
700	3500	73.030 ± 5.289
700	4500	72.467 ± 5.477
700	5500	73.473 ± 5.538
700	6500	76.003 ± 4.676

C. EFFECTS OF ILLUMINANCE AND COLOR TEMPERATURE ON THE NON-VISUAL STATE INDEX I AND IDENTIFICATION OF THE PREFERRED THRESHOLD FOR NON-VISUAL EFFECTS

The repeated-measures analysis of variance results for the non-visual state index I showed that the main effect of illuminance was significant ($F = 300.434$, $p < 0.001$), the main effect of color temperature was significant ($F = 149.654$, $p < 0.001$), and the interaction effect between illuminance and color temperature was also significant ($F = 3.696$, $p = 0.002$). Compared with technical compliance, both the illuminance and color temperature main effects on I were stronger, indicating that non-visual indicators are more sensitive to changes in lighting parameters. Therefore, it is necessary to take the non-visual state index I as an independent mainline for threshold identification. Specifically, the high-value region of the non-visual state index I was concentrated in the 5500K row, covering the 500lx and 700lx illuminance levels, as shown in Figure 5.

The descriptive statistics of the non-visual state index I are shown in Table 6. The highest combination for the non-visual state index I was 700lx + 5500K (0.686 ± 0.078),



(a) Heat map of technical compliance (b) Marginal trend plot of technical compliance

FIGURE 4. The variation characteristics of technical compliance under different illuminance and color

followed by 500lx + 5500K (0.682 ± 0.050). Using "no significant difference from the optimal combination" as the criterion for the preferred interval, the results showed that 500lx + 5500K ($p = 0.807$), which was not significantly different from 700lx + 5500K, was included in the optimal combination set. This result indicates that the optimum non-visual state is more concentrated in the balanced region of medium-to-high illuminance and medium-to-high color temperature, rather than at the highest color temperature point.

TABLE 6. Descriptive statistics of the non-visual state index I under 12 lighting conditions

Illuminance (lx)	Color Temperature (K)	Mean ± Standard Deviation
300	3500	0.329 ± 0.070
300	4500	0.472 ± 0.077
300	5500	0.510 ± 0.079
300	6500	0.400 ± 0.063
500	3500	0.431 ± 0.073
500	4500	0.543 ± 0.046
500	5500	0.682 ± 0.050
500	6500	0.503 ± 0.057
700	3500	0.482 ± 0.042
700	4500	0.586 ± 0.072
700	5500	0.686 ± 0.078
700	6500	0.559 ± 0.079

D. CORRELATION BETWEEN TECHNICAL COMPLIANCE AND THE NON-VISUAL STATE INDEX I AND DETERMINATION OF THRESHOLD INTERSECTION

The correlation between technical compliance and the non-visual state index I was compared, as shown in Table 6. The paper reports a Pearson correlation of $r = 0.0585$ ($p = 0.268$) between technical compliance and the non-visual state index I, concluding that the two are "not completely synchronized". However, it is important to note that this non-significant correlation may be subject to limitations. Specifically, while the study involved 360 data points, the sample size might still be insufficient to detect very small correlations. Furthermore, the relationship between light environment and complex athletic performance may be non-linear, which could mask associations in a standard Pearson analysis. Future research should further explore these variables with larger cohorts and non-linear modeling. This indicates that the optimum non-visual state and the optimum sports performance are not completely synchronized, and the two do not constitute a single objective that can substitute for each other. If lighting parameters are determined solely on the basis of sports performance, athletes may easily experience fatigue, poor mood, and other problems during exercise. Therefore, the lighting design of university table tennis courts needs to take into account dual-dimensional parameter optimization rather than pursuing sports performance alone.

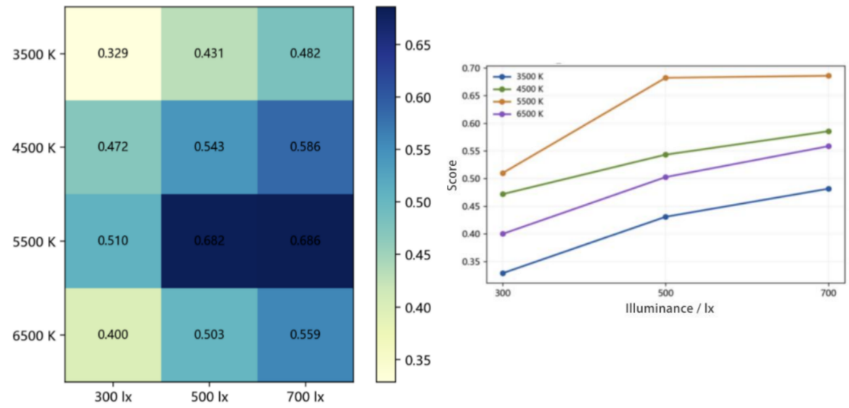
From the preferred sets, the preferred combinations for technical compliance were concentrated at 6500 K, while the preferred combinations for the non-visual state index I were concentrated at 5500 K. The two had partially overlapping intervals at the illuminance level, namely 500lx and 700lx, but no strict overlap was formed at the color temperature level. This further confirms that lighting optimization faces a dual-objective trade-off between "favoring sports performance" and "favoring non-visual state": if a better non-visual state is pursued, 5500 K has more advantages; if technical compliance is emphasized, 6500 K has more advantages.

TABLE 7. Correlation results between Technical compliance and Comprehensive State Index I

Variable Pair	Correlation Coefficient r	p Value
Technical compliance vs non-visual state index I	0.0585	0.268

E. CONTINUOUS REGRESSION FOR THE INTEGRATED OBJECTIVE

Previous correlation analyses confirmed no significant correlation between technical compliance and the non-visual state index I. Moreover, their optimal thresholds were characterized by differentiated preferences in correlated color



(a) Heat map of the non-visual state index I (b) Marginal trend plot of the non-visual state index I

FIGURE 5. The variation characteristics of non-visual state index I under different illuminance and color temperature conditions

temperature (CCT) and overlapping ranges in illuminance. Accordingly, this study adopted a comprehensive objective optimization strategy. First, technical compliance and the non-visual state index I were standardized separately. Their weights in the overall synthesis were determined via the CRITIC objective weighting method, as shown in Table 8. On this basis, the comprehensive objective function was constructed as: $J=0.5531\times S+0.4469\times I$. where S denotes the standardized score of technical compliance and I denotes the standardized score of the non-visual state index. This function served as the core optimization objective. Meanwhile, illuminance and CCT were treated as continuous independent variables. A quadratic response surface regression model was employed to fit and optimize the relationship between the independent variables and the comprehensive objective function J.

TABLE 8. top-level CRITIC weights of technical compliance and the non-visual state index I

Indicator	Standard Deviation	Conflict	Information Content	Weight
Technical Compliance	0.222	0.941	0.209	0.554
Index I	0.180	0.941	0.169	0.447

The response surface results for the comprehensive objective J ($R^2 = 0.735$) are illustrated in Figure 6. The high-value regions of the comprehensive objective for lighting in university table tennis venues are concentrated at an illuminance of approximately 700 lx and a correlated color temperature of 6000 K. Model optimization within the experimental range identifies the optimal parameter combination: 700 lx and 5800 K. This lighting scheme enables a balanced optimization between athletic performance and non-visual effects.

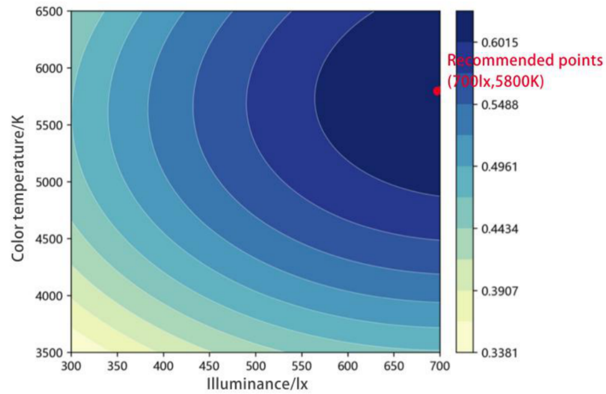


FIGURE 6. shows the continuous response surface and recommended points of the comprehensive objective J

IV. CONCLUSION

(1) The optimal threshold for athletic performance was determined as a high correlated color temperature (CCT) of 6500 K and a medium-to-high illuminance range of 500–700 lx. For non-visual effects, the optimal threshold corresponded to a medium-high CCT of 5500 K and the same medium-to-high illuminance range of 500–700 lx. The two objectives thus exhibited differentiated CCT preferences yet overlapping illuminance intervals. After establishing the comprehensive objective function via the CRITIC objective weighting method and performing optimization using quadratic response surface regression, the optimal lighting parameters balancing both athletic performance and non-visual effects were identified as 700 lx and 5800 K. This combination can maintain satisfactory athletic performance while improving the non-visual state of athletes, providing a scientific and human-centered quantitative basis for lighting design in university table tennis facilities and similar indoor small-ball sports venues.

(2) Future research may expand the sample size and age range of participants, and include more indoor small-

ball sports such as badminton and billiards to improve the population applicability and generalizability of the findings. In addition, quantitative indicators characterizing non-visual photobiological effects (e.g., EML, CS, mEDI) can be introduced, combined with more objective physiological indices such as heart rate variability (HRV) and cortisol levels. Long-term exposure experiments under different light environments can be conducted to further reveal the mechanisms underlying the effects of illuminance, CCT, and other non-visual lighting parameters on athletic performance and non-visual responses. This would provide more comprehensive theoretical support for the refined and human-centric design of light environments in sports buildings.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Ethics Committee of Hebei University of Engineering, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

AUTHOR CONTRIBUTIONS

Conceptualization –Shouyi Wang, Zixuan Wang and Xiaoying Wang; methodology – Shouyi Wang, Zixuan Wang and Xiaoying Wang; investigation – Shouyi Wang, Zixuan Wang and Xiaoying Wang; writing-original draft preparation – Shouyi Wang, Zixuan Wang and Xiaoying Wang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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