

## Article

# Effects of the Light Environment on Visual Comfort and Perceptual Preference in Static Exhibition Spaces of History Museums

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## Abstract

History museum exhibition spaces convey historical and cultural information through static artifacts, graphic–text narratives, and spatial atmosphere. The light environment affects not only exhibit visibility but also visitors’ visual comfort and perceptual preference. However, existing studies mainly focus on single lighting parameters, and perceptual differences across multiple lighting conditions remain insufficiently understood. This study investigated static exhibition spaces in history museums through a comparison of 12 virtual lighting conditions generated from different combinations of ambient illuminance, exhibit illuminance, and correlated color temperature. Visitors’ visual behavior and subjective perception were evaluated through eye-tracking experiments, heatmap analysis, and Likert-scale ratings. Different lighting combinations significantly affected visual attention allocation and subjective evaluation. Total duration of fixation, number of fixations, and average pupil diameter showed significant differences across conditions, whereas average fixation time did not. Overall, moderate ambient illuminance and higher exhibit illuminance were associated with more stable visual responses and more positive perceptual evaluations, while correlated color temperature showed a regulatory effect within the tested range of 3000–4000 K. These findings provide preliminary evidence for understanding perceptual responses to lighting combinations in static exhibition spaces and may inform future field-based validation of museum lighting design.

**Keywords:** history museums; static exhibition spaces; light environment; visual comfort; perceptual preference; eye tracking



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## 1. Introduction

As important cultural carriers linking the past, present, and future, history museums not only display artifacts and narrate history through their exhibition spaces, but also directly affect visitors’ information acquisition efficiency, quality of visual perception, and overall visiting experience [1]. Existing studies have shown that display forms, spatial organization, and environmental cues in museums significantly influence visitors’ visual experience and emotional responses. History museums, in particular, require appropriate spatial expression and environmental design to achieve a balance among cultural information delivery, atmosphere construction, and visitor cognitive engagement [2]. At the same time, although recent studies have increasingly emphasized the human-centered orientation of spatial experience, research on visual perception still focuses mainly on

spatial organization, display forms, or single visual factors. Sufficient empirical evidence is still lacking regarding perceptual differences across lighting conditions composed of ambient illuminance, exhibit illuminance, and correlated color temperature, which are key lighting variables directly involved in the viewing process [3]. Previous studies have also indicated that relying solely on technical parameter optimization or subjective judgment makes it difficult to fully reveal the complex interaction among light, space, and humans. In contrast, combining eye tracking with subjective evaluation makes it possible to record both viewers' visual paths and subjective feedback, thereby providing a more accurate explanation of the formation mechanism of visual comfort [4,5].

Therefore, this study takes static exhibition spaces in history museums as the research object. It compares 12 virtual lighting conditions generated from different combinations of ambient illuminance, exhibit illuminance, and correlated color temperature, and uses eye-tracking experiments and subjective evaluation methods to examine differences in visual comfort and perceptual preference under these conditions.

### *1.1. Forms of Historical Exhibition Design*

In recent years, museum exhibition research has gradually shifted from “collection display” to a comprehensive perspective that integrates narrative organization, spatial experience, and audience participation. Exhibitions are not merely displays of objects, but also an ongoing process of knowledge production and public participation [6]. Digital technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) are continuously expanding the boundaries of museum display [7]. Comparisons between the real and virtual Pitt Rivers Museum have shown that virtual exhibitions mainly strengthen information acquisition and remote access functions, but do not alter the basic viewing logic of physical exhibitions [8]. Virtual exhibitions are also considered more suitable as supplementary platforms for physical museums [9]. Interactive VR helps enhance educational communication and audience participation [10], while virtual reconstruction has unique value in preserving temporary exhibitions and extending them beyond their physical duration [11].

Compared with research on digital exhibitions, studies on physical exhibitions in history museums pay greater attention to display forms and spatial organization. Different display forms significantly affect information processing and perceptual evaluation, and “3D scenes + real objects” are more likely to yield higher satisfaction and preference, whereas “images + real objects” are more conducive to short-term cognition [12]. Spatial integration, passage organization, and route depth influence movement patterns and dwell-time distribution [13]. In addition, circulation type, node setting, and turning mode affect browsing efficiency [14]. Historical remains, artifact display, and cultural symbols are important factors influencing visits to heritage museums, whereas crowding, queuing, and unclear circulation are more likely to lead to negative evaluations [15].

Overall, although the exhibition design of history museums has continuously incorporated digital media and interactive technologies, its core still lies in the coordination among physical exhibits, interpretive information, and spatial organization [7]. Compared with highly immersive or strongly interactive digital exhibitions, static conventional exhibitions better reflect the typical display characteristics of history museums and are also more suitable as baseline settings for analyzing the effects of environmental variables [12]. In addition, spatial circulation, node guidance, and combinations of display forms have been shown to influence viewing paths and perceptual experience [13,14]. Therefore, this study selects static conventional exhibitions as the study context. This type of setting is consistent with the actual exhibition context of history museums and is also conducive

to identifying the influence mechanism of the light environment on visual comfort and perceptual preference under controlled conditions [15].

### 1.2. Research on Museum Light Environment Design

Research on museum light environments initially centered on artifact conservation. A review of this field has shown that it has gradually formed a basic research framework has gradually formed around light-damage control, lighting quality, and energy-saving optimization [16]. The key factor determining artifact damage is not simply the light source type, but rather its spectral distribution [17]. A series of subsequent studies further developed quantitative approaches to museum lighting, including spectral damage modeling for sensitive materials, illuminance-based evaluation of paintings, correlated color temperature indexing for polychrome artworks, and optimal LED spectra for heritage materials [18–21].

As this field has developed, the focus of museum lighting studies has gradually shifted from “conservation first” to a balanced concern for conservation and presentation. Joint investigations of illuminance and correlated color temperature in simulated exhibition halls have proposed lighting indicators for Chinese paintings that consider both conservation standards and color preference [22]. Color-preference evaluation methods for traditional Chinese paintings have also been established based on light source spectral analysis, and key wavelength bands affecting preference have been identified [23]. In addition, photodamage prediction models for polychrome relics and tunable white-light systems have been developed to achieve the coordinated optimization of conservation and lighting performance [24]. Related studies have further emphasized that museum lighting should not be treated solely as a technical conservation issue, but also as a medium that shapes curatorial interpretation and visual perception [25,26]. Some research has also examined daylighting effectiveness, risks to artifacts, and visual comfort in museum or heritage-museum settings, thereby extending the discussion from electric lighting to the overall luminous environment of exhibition spaces [27]. More recent work has explored spectral image processing and computational approaches for museum lighting evaluation and optimization [28]. Beyond material conservation, visual experience has also received increasing attention. Field experiments have shown that lighting configurations with an appropriate brightness contrast between exhibits and background are more likely to generate a positive visual experience [29]. In addition, models have been proposed to address complex luminance distributions in exhibition halls and to make lighting evaluation more applicable to museum contexts [30]. Furthermore, adaptive lighting control based on target recognition has been achieved by combining convolutional neural networks with tunable luminaires [31].

Overall, research on museum light environments has expanded from early threshold control centered on artifact conservation to multiple dimensions, including overall light quality, viewing experience, curatorial expression, and intelligent lighting optimization [16]. However, existing studies still focus mainly on highly photosensitive objects such as paintings, paper relics, and polychrome artifacts, while relatively less attention has been paid to static, integrated exhibition settings commonly found in history museums [18,21,22]. Meanwhile, most existing studies approach the issue from single spectral indicators, correlated color temperature indicators, or conservation indicators, and relatively few discuss spatial viewing experience from the combined perspective of ambient illuminance, exhibit illuminance, and correlated color temperature [20,23]. Although related studies have increasingly addressed luminance contrast, glare, and visual experience [29–31], empirical work integrating observed visual behavior with subjective evaluation remains limited. Therefore, this study discusses the mechanism through which the light environment affects visual comfort and perceptual preference in static exhibition spaces of history museums

in relation to three lighting parameters: ambient illuminance, exhibit illuminance, and correlated color temperature. In doing so, it supplements existing research in terms of research object and comparison across multiple lighting conditions.

### *1.3. Combined Method of Eye Tracking and Subjective Evaluation*

Museum visiting research has often used questionnaires, semantic evaluation, and interviews to assess user experience. These methods can reflect outcome-based judgments of comfort, preference, atmosphere, and restoration, but they reveal relatively little about the distribution of visual attention, dwell characteristics, and gaze-shift patterns during the viewing process [2]. With the development of eye-tracking and visual perception methods, an increasing number of studies have introduced eye-tracking technology into the evaluation of spatial experience. Eye-tracking indicators can capture processes such as attention allocation, visual search, and cognitive load, thus providing process-based evidence for spatial perception research [4]. In studies of display forms in history museums, the combination of eye-tracking and subjective evaluation has shown that different display modes not only lead to differences in fixation duration and fixation count, but also produce differences in satisfaction and preference ratings [12]. Research on museum visitor experience has further shown that relying solely on a single type of subjective evaluation is insufficient to fully explain the visiting process, because behavioral data and interview results show clear complementarity [32]. Objective measurements can also provide supplementary evidence for subjective judgments in studies of museum immersion [33]. Similarly, combined “subjective questionnaire–eye-tracking experiment” approaches have been applied in research on spatial light environments to comprehensively analyze visual comfort and safety perception, thereby confirming the applicability of this method in multi-condition studies of complex spatial environments [34].

Overall, subjective evaluation is more suitable for measuring overall judgments of spatial brightness, hierarchy, comfort, and preference, whereas eye-tracking data can further reflect process-based characteristics such as fixation distribution, visual dwell, and pupil response under different lighting conditions [4]. The combination of the two helps improve the objectivity of visual perception research and also allows a more complete explanation of the mechanism through which environmental factors affect experiential responses [32,33]. Therefore, in the context of static conventional exhibition scenes in history museums, this study adopts a combined method of eye-tracking experiments and post-experiment subjective evaluation to comprehensively analyze the effects of ambient illuminance, exhibit illuminance, and correlated color temperature on visual comfort and perceptual preference.

## **2. Materials and Methods**

### *2.1. Research Method*

This study adopted a combined approach of subjective evaluation and eye tracking to investigate the effects of different light environment parameters on viewers’ visual comfort and perceptual preference in static exhibition spaces of history museums. Based on a unified history museum exhibition hall scene, the study constructed 12 virtual lighting conditions by combining different levels of ambient illuminance, exhibit illuminance, and correlated color temperature. Eye-tracking indicators, heatmap analysis, and Likert-scale results were then combined to comprehensively evaluate visual behavior and subjective perception under different lighting conditions. To clearly present the implementation process and analytical logic of this study, a technical roadmap was drawn, as shown in Figure 1. Starting from the literature review and variable determination, the diagram sequentially presents the complete research process, including virtual scene construction,

stimulus generation, eye-tracking experiment implementation, subjective and objective data collection, statistical analysis, and the extraction of optimization strategies. The virtual scenes were used as controlled experimental stimuli to compare relative perceptual differences among lighting conditions, rather than to fully reproduce the complex optical environment of real museum spaces.

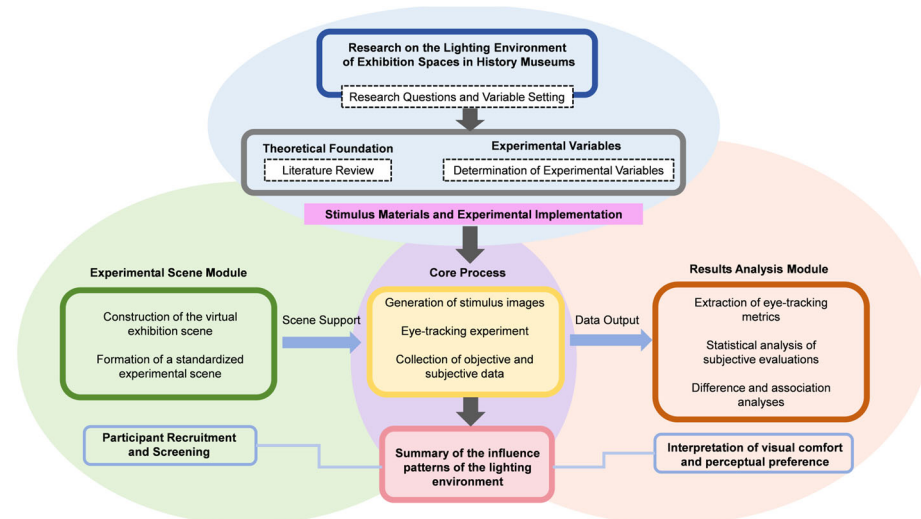


**Figure 1.** Research framework of this study. The black arrows indicate the main sequential workflow of the study, and the blue arrows indicate supporting relationships between modules.

## 2.2. Participants

A total of 32 participants were recruited through open recruitment, including 12 undergraduate students, 12 graduate students, and 8 members of the general public. All participants had normal or corrected-to-normal vision, had no color blindness or color weakness, and were able to complete the experimental task. To reduce experience bias, none of the participants had previously been exposed to the experimental stimuli used in this study. Before the experiment began, all participants signed written informed consent forms and were informed that the eye-tracking data would be used only for academic research. After data quality screening, 29 valid samples were finally included in the subsequent statistical analysis. The final valid sample included 12 males and 17 females, aged 20–50 years, with a mean age of  $25.41 \pm 7.26$  years. Most participants were undergraduate or graduate students aged 20–25 years, while three participants were professional mentors aged 42–50 years.

## 2.3. Experimental Equipment and Data Collection

Eye-tracking data were collected using SMI ETG2W eye-tracking glasses (SensoMotoric Instruments GmbH, Teltow, Germany), with a sampling rate of 120 Hz. The experiment was conducted in a laboratory at Nanjing Forestry University to control external environmental conditions (Figure 2). During the experiment, the curtains were closed to block daylight and avoid direct sunlight. Only stable electric lighting in the laboratory was used, and the ambient room lighting was kept consistent for all participants. Before the formal experiment, the ambient illuminance was measured under a black-screen condition at the participant's viewing position, approximately 65 cm from the monitor and at the participant's eye level. Because the Konica Minolta Illuminance Meter T-10M (Konica Minolta Sensing, Inc., Tokyo, Japan) used in this study only recorded illuminance, the correlated color temperature of the laboratory lighting was not systematically recorded. After data collection, SMI BeGaze 3.7 (SensoMotoric Instruments GmbH, Teltow, Germany) was used

to collect and analyze the eye-tracking data. Eye-tracking recordings were screened before statistical analysis, and recordings with a valid gaze data ratio lower than 70% were excluded. As a result, three recordings were excluded, and 29 valid samples were retained for subsequent analysis. Based on previous studies [35], this study selected four eye-tracking indicators as the main analytical variables: total duration of fixation, average fixation time, number of fixations, and average pupil diameter. The definitions of these indicators are shown in Table 1.

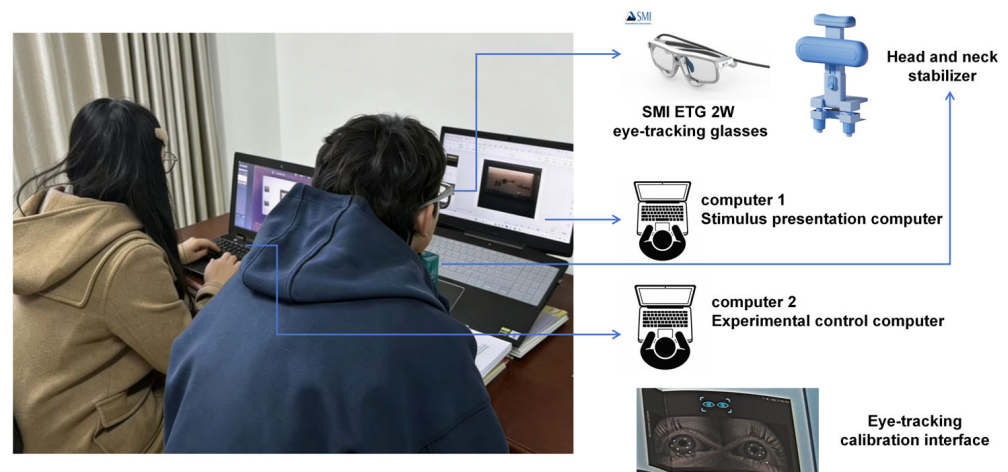


**Figure 2.** Experimental setting and equipment configuration.

**Table 1.** Meanings and definitions of eye-tracking indicators.

| Indicator Name             | Abbreviation | Meaning                                                                                                  |
|----------------------------|--------------|----------------------------------------------------------------------------------------------------------|
| Total duration of fixation | TDOF         | Reflects the overall degree of visual engagement of viewers in the target area.                          |
| Average fixation time      | AFT          | Reflects the information-processing intensity and fixation stability of a single fixation.               |
| Number of fixations        | NOF          | Reflects the frequency of viewers' attention to the target area and the activity level of visual search. |
| Average pupil diameter     | APD          | Reflects an auxiliary photophysiological response related to relative visual stimulus strength.          |

#### 2.4. Research Object

Taking representative traditional historical exhibition halls in several museums in China as reference prototypes, this study extracted their spatial forms, methods of displaying physical exhibits, and light environment characteristics, and then constructed a unified experimental scene. First, Autodesk 3ds Max 2024 (Autodesk Inc., San Francisco, CA, USA) was used to complete the three-dimensional modeling and rendering of the exhibition hall space, display interface, and exhibit arrangement, thereby generating the visual stimuli required for the experiment. Representative scenes are shown in Figure 3. On this basis, DIALux evo 13.2 (DIAL GmbH, Lüdenscheld, Germany) was further used to simulate, calibrate, and verify the ambient illuminance and exhibit illuminance in the scene to ensure that the lighting parameters in the experimental conditions corresponded as accurately as possible to the preset values. Representative illuminance analysis results are shown in Figure 3.

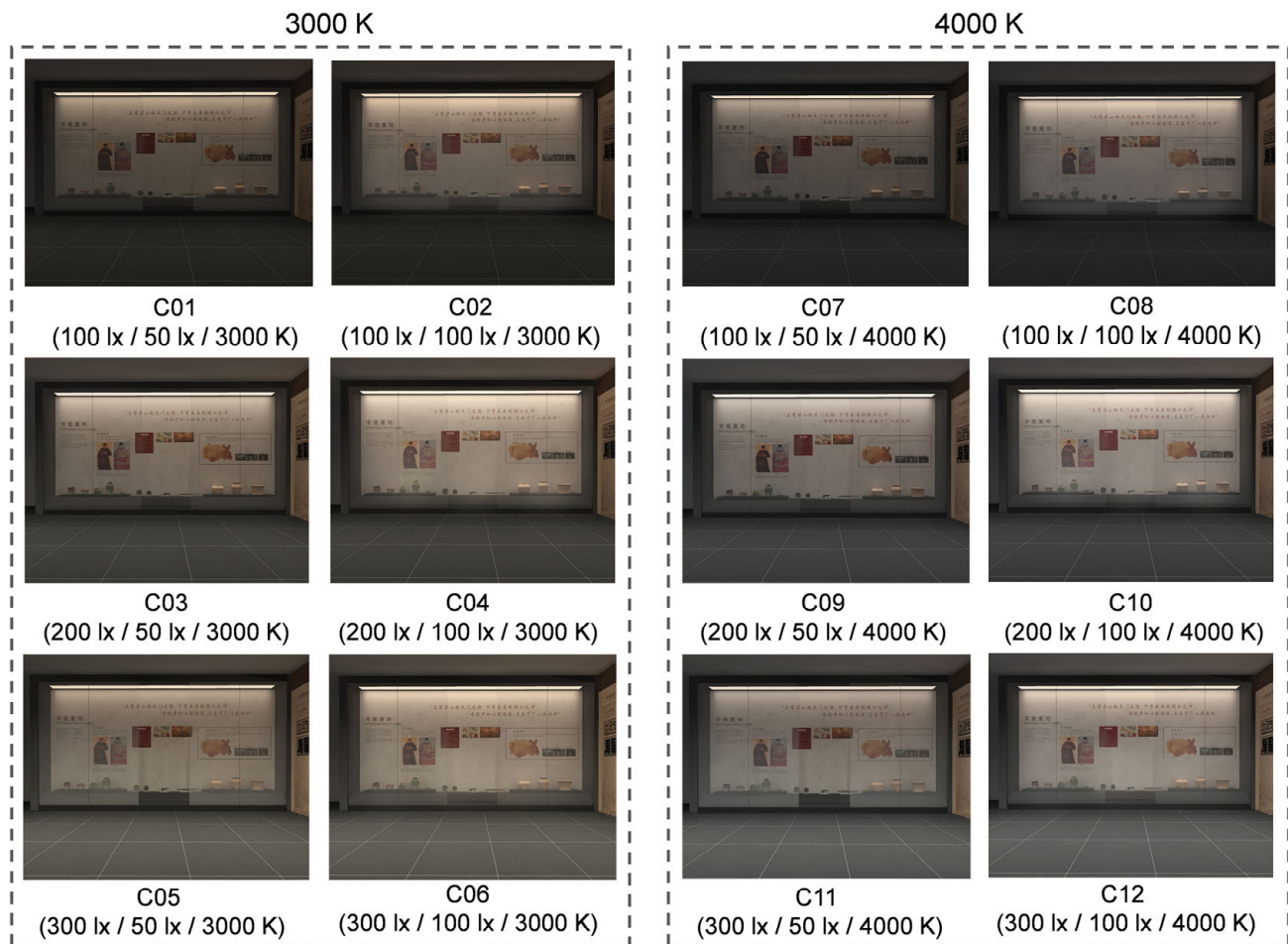


**Figure 3.** Experimental design and visual stimulus matrix under 12 lighting conditions. The Chinese text in the images is part of the simulated historical exhibition content.

The experiment constructed 12 stimulus scenes representing different combinations of ambient illuminance, exhibit illuminance, and correlated color temperature. Specifically, ambient illuminance was set at 100 lx, 200 lx, and 300 lx; exhibit illuminance was set at 50 lx and 100 lx; and correlated color temperature was set at 3000 K and 4000 K. In the DIALux simulation, ambient illuminance values of 100 lx, 200 lx, and 300 lx were evaluated as the average illuminance on the general exhibition background area, excluding the locally emphasized exhibit surfaces. Exhibit illuminance values of 50 lx and 100 lx were evaluated as the average illuminance on the main exhibit/display surfaces. Thus, these illuminance levels represent simulated values within the virtual scene rather than measurements taken in the physical laboratory. This resulted in 12 experimental conditions, labeled C01–C12. The specific parameters and coding are shown in Figure 3. Except for the target variables, all scenes were kept consistent in exhibition layout, exhibit content, material interface, and viewing angle so as to reduce interference from non-experimental factors. Through the corresponding verification of rendered images and DIALux illuminance analysis diagrams, consistency and controllability of the experimental stimuli in both visual presentation and illuminance distribution were ensured (Figure 4).

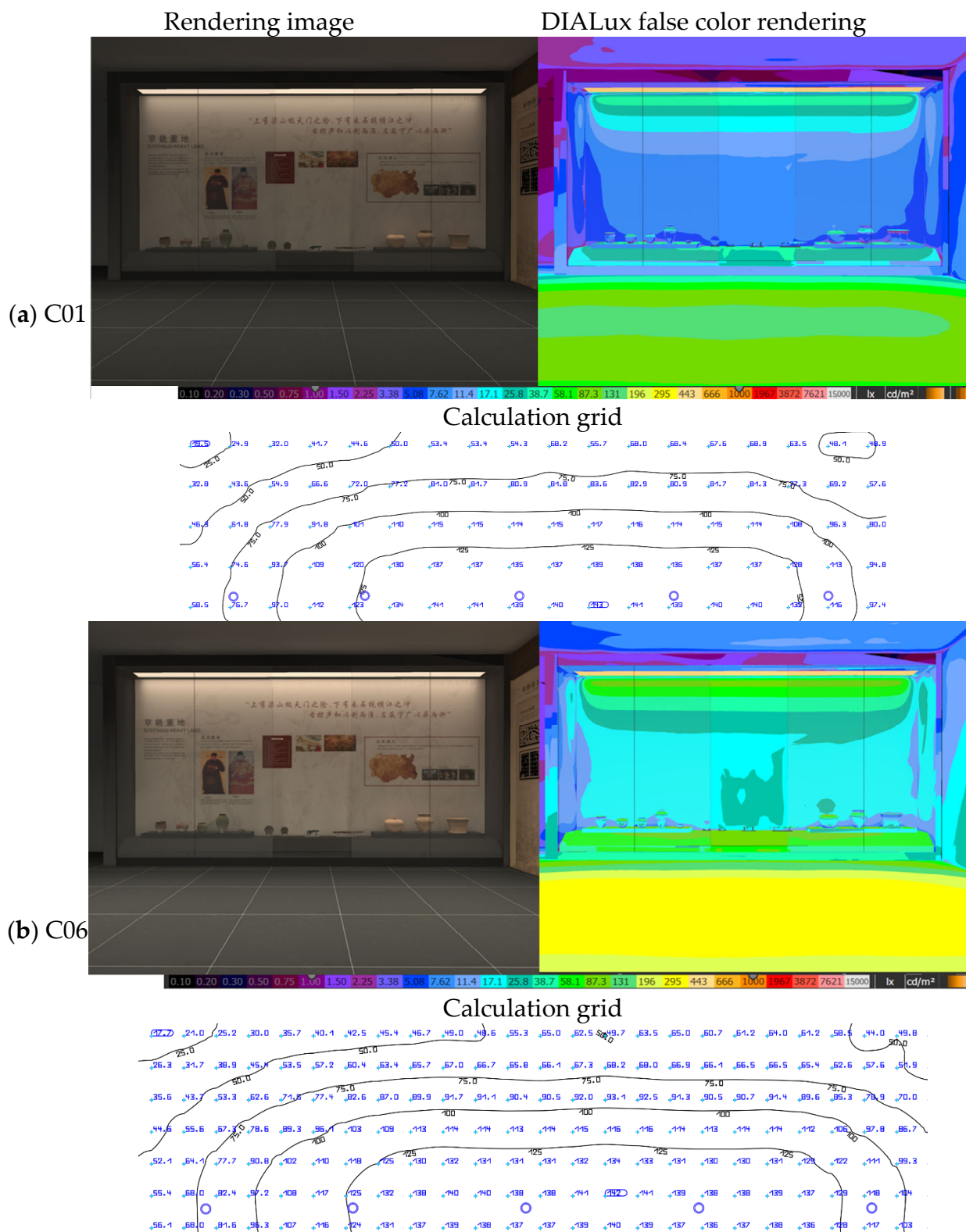


**Figure 4.** DIALux false-color illuminance maps of representative scenes. The Chinese text appearing in the rendered scenes is part of the simulated historical exhibition content.

## 2.5. Experimental Procedure

Before the formal experiment began, participants completed an experimental information form. After being informed of the experiment, the basic procedure, and relevant precautions, they removed their glasses when required and wore the eye-tracking device,

after which equipment calibration was completed. After successful calibration, participants independently viewed the randomly presented stimulus images under controlled laboratory conditions. To control non-experimental variables, all stimulus images were presented full-screen on a Dell G3 laptop display (Dell Inc., Round Rock, TX, USA) with a resolution of  $1920 \times 1080$  pixels, and the viewing distance was approximately 65 cm. Each image was shown for 15 s, and a 3-s black screen was inserted between adjacent images to indicate scene switching and reduce the residual influence of the preceding stimulus. During the experiment, participants were asked to view the scenes attentively and to experience the scenes and to avoid additional cognitive tasks as much as possible, so as to minimize the effects of memory, emotional fluctuations, and differences in attention allocation on the eye-tracking results. After all stimuli had been presented, participants completed the Likert-scale questionnaire for the 12 scenes. To reduce scene confusion and recency bias, each questionnaire item was accompanied by the corresponding scene code and thumbnail image, allowing participants to refer back to the specific scene when providing ratings. In addition, the 12 stimulus images were presented in a randomized order across participants to reduce systematic order effects. The entire experiment was conducted in a quiet environment, and the experimental procedure is shown in Figure 5. Statistical analyses were performed using IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA), including repeated-measures ANOVA, Bonferroni-corrected pairwise comparisons, Friedman tests, Kendall's W, and Pearson correlation analysis.

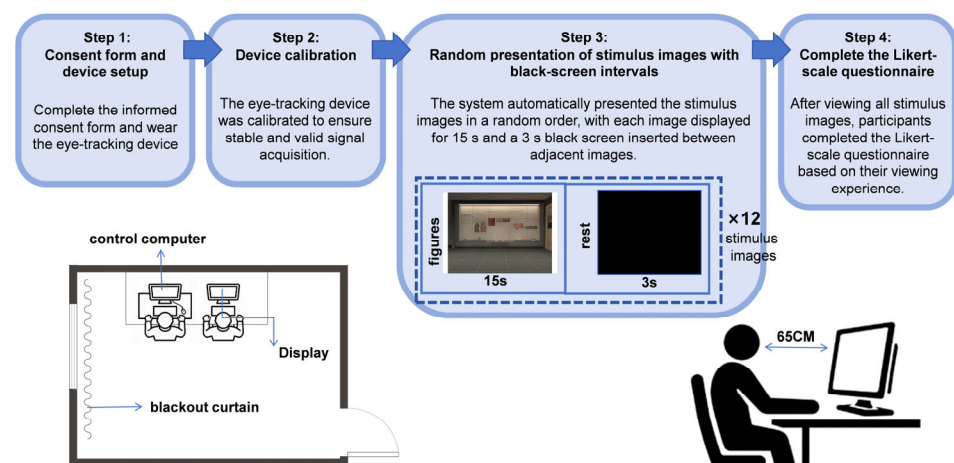


**Figure 5.** Formal experimental procedure and experimental environment. The Chinese text appearing in the rendered scenes is part of the simulated historical exhibition content.

### 3. Results

#### 3.1. Analysis of Differences in Eye-Tracking Indicators Under Different Lighting Conditions

To compare the effects of different lighting conditions on viewers' visual behavior, this study selected total duration of fixation (TDOF), number of fixations (NOF), average fixation time (AFT), and average pupil diameter (APD) as the main eye-tracking indicators and conducted a repeated-measures analysis of variance (ANOVA) with lighting condition treated as a 12-level within-subject factor. Descriptive statistics are shown in Table 2, assumption test results are shown in Table 3, and the ANOVA results are shown in Table 4. The results indicated that lighting conditions had significant effects on TDOF, NOF, and APD ( $p < 0.05$ ), but not on AFT ( $p > 0.05$ ). Therefore, the subsequent analysis focused mainly on TDOF, NOF, and APD, which were interpreted in combination with heatmap results and subjective evaluations.

**Table 2.** Descriptive statistics of eye-tracking indicators under different lighting conditions ( $n = 29$ ).

| Condition | TDOF (ms, $M \pm SD$ )  | NOF (Times, $M \pm SD$ ) | AFT (ms, $M \pm SD$ ) | APD (mm, $M \pm SD$ ) |
|-----------|-------------------------|--------------------------|-----------------------|-----------------------|
| C01       | 11,125.08 $\pm$ 3339.22 | 46.00 $\pm$ 10.77        | 255.71 $\pm$ 108.05   | 4.25 $\pm$ 0.660      |
| C02       | 10,470.67 $\pm$ 2938.07 | 43.72 $\pm$ 10.55        | 253.46 $\pm$ 99.30    | 4.18 $\pm$ 0.682      |
| C03       | 10,421.32 $\pm$ 2694.00 | 42.28 $\pm$ 9.54         | 257.53 $\pm$ 94.56    | 4.16 $\pm$ 0.680      |
| C04       | 11,046.27 $\pm$ 3481.09 | 41.79 $\pm$ 9.48         | 277.59 $\pm$ 120.20   | 4.00 $\pm$ 0.655      |
| C05       | 10,663.87 $\pm$ 3145.16 | 43.21 $\pm$ 14.97        | 293.72 $\pm$ 230.28   | 4.13 $\pm$ 0.623      |
| C06       | 10,357.67 $\pm$ 2984.27 | 42.76 $\pm$ 10.61        | 252.11 $\pm$ 113.51   | 4.08 $\pm$ 0.642      |
| C07       | 10,624.79 $\pm$ 3719.05 | 42.76 $\pm$ 12.82        | 261.09 $\pm$ 116.92   | 4.24 $\pm$ 0.615      |
| C08       | 9662.94 $\pm$ 3161.09   | 39.59 $\pm$ 11.63        | 273.35 $\pm$ 174.91   | 4.20 $\pm$ 0.735      |
| C09       | 9651.81 $\pm$ 4391.68   | 40.03 $\pm$ 17.60        | 263.30 $\pm$ 165.02   | 4.10 $\pm$ 0.657      |
| C10       | 9502.69 $\pm$ 2807.12   | 41.10 $\pm$ 11.75        | 236.29 $\pm$ 88.65    | 3.98 $\pm$ 0.622      |
| C11       | 9335.25 $\pm$ 3434.26   | 39.62 $\pm$ 12.26        | 241.93 $\pm$ 115.79   | 4.16 $\pm$ 0.725      |
| C12       | 9834.44 $\pm$ 3407.14   | 37.24 $\pm$ 12.28        | 275.68 $\pm$ 123.65   | 4.01 $\pm$ 0.627      |

**Table 3.** Assumption tests for ANOVA.

| Statistical Indicators | Shapiro–Wilk $p$ Range | Normality Summary                | Levene’s $p$ | Homogeneity Result |
|------------------------|------------------------|----------------------------------|--------------|--------------------|
| TDOF (ms)              | 0.001–0.666            | Deviations in several conditions | 0.898        | Not violated       |
| NOF (N)                | <0.001–0.991           | Satisfied in most conditions     | 0.546        | Not violated       |
| AFT (ms)               | <0.001–0.134           | Deviations in several conditions | 0.536        | Not violated       |
| APD (mm)               | 0.095–0.870            | Satisfied in all conditions      | 0.993        | Not violated       |

**Table 4.** Repeated-measures ANOVA results of eye-tracking indicators under different lighting conditions.

| Statistical Indicators | Source           | Mean Square   | F     | $p$    |
|------------------------|------------------|---------------|-------|--------|
| TDOF (ms)              | Condition effect | 10,714,010.15 | 2.914 | 0.001  |
|                        | Error            | 3,677,071.54  |       |        |
| AFT (ms)               | Condition effect | 7544.11       | 1.063 | 0.391  |
|                        | Error            | 7098.45       |       |        |
| NOF (N)                | Condition effect | 156.16        | 1.99  | 0.029  |
|                        | Error            | 78.491        |       |        |
| APD (mm)               | Condition effect | 0.244         | 6.399 | <0.001 |
|                        | Error            | 0.038         |       |        |

Before conducting repeated-measures ANOVA, the assumptions of normality and homogeneity of variance were examined. Normality was assessed using the Shapiro–Wilk test for each eye-tracking indicator under each lighting condition, and homogeneity of variance across the 12 lighting conditions was examined using Levene’s test. The results are summarized in Table 3. APD met the normality assumption across all 12 conditions, while NOF met this assumption in most conditions. Deviations from normality were observed in several conditions for TDOF and AFT. Levene’s test indicated that the homogeneity of variance assumption was not violated for any of the four eye-tracking indicators.

From the perspective of total duration of fixation, significant differences were observed among scenes, indicating that changes in the light environment affected viewers’ overall visual engagement with the exhibition scene. As shown in Table 2 and Figure 6, the mean TDOF values varied noticeably under different combinations of ambient illuminance, exhibit illuminance, and correlated color temperature. Higher total fixation duration under

some conditions indicated that viewers invested more visual attention in those scenes. However, this indicator should not be interpreted as direct evidence of optimal visual comfort was optimal and still needed to be judged together with fixation distribution characteristics and pupil response.

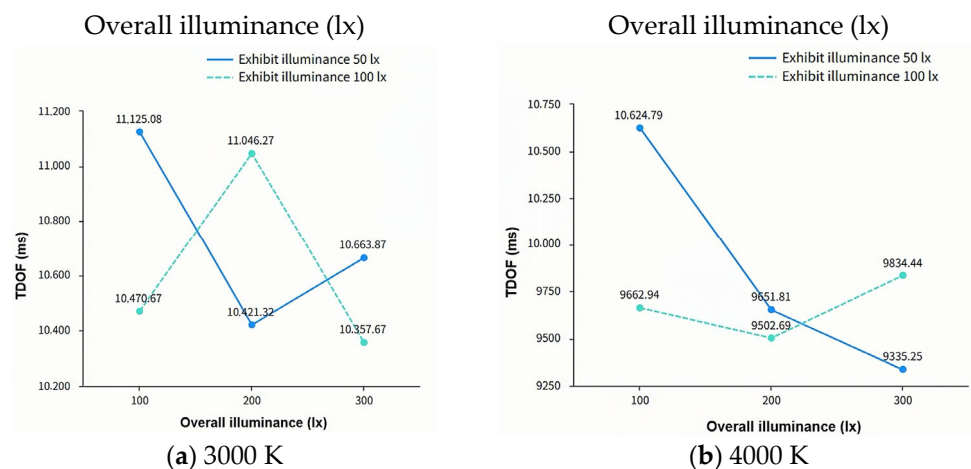


**Figure 6.** Mean trend of TDOF under different correlated color temperature (CCT) conditions. (a) 3000 K; (b) 4000 K.

The significant differences in the number of fixations indicated that different lighting conditions altered viewers' visual search patterns and attention allocation. As shown in Figure 7, NOF displayed different trends across conditions. A higher number of fixations may indicate more active visual exploration, but it may also reflect frequent searching caused by an unclear hierarchy between the exhibits and the background.

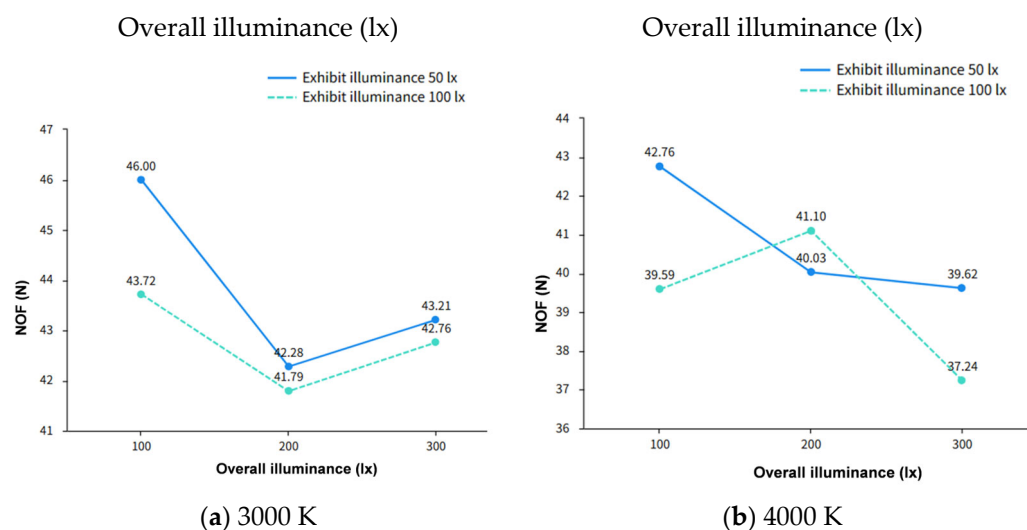


**Figure 7.** Mean trend of NOF under different correlated color temperature (CCT) conditions. (a) 3000 K; (b) 4000 K.

Average pupil diameter (APD) showed the most significant differences across conditions, indicating that it was sensitive to changes in the light environment. However, because APD is directly influenced by retinal luminance flux, it should be interpreted as a photophysiological response related to relative visual stimulus strength rather than as direct evidence of visual comfort or cognitive load. As shown in Table 2 and Figure 8, APD showed clear differences in its distribution under different conditions. Therefore, APD was interpreted together with fixation indicators, heatmap distribution, and subjective evaluations.

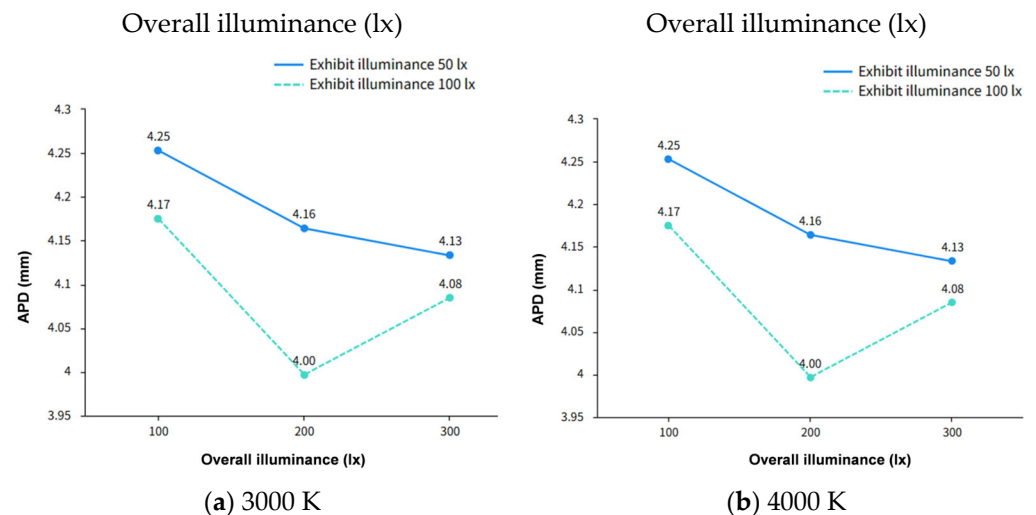


**Figure 8.** Mean trend of APD under different correlated color temperature (CCT) conditions. (a) 3000 K; (b) 4000 K.

Further examination of the mean performance of the 12 conditions showed that the relationship among ambient illuminance, exhibit illuminance, and correlated color temperature did not follow a simple pattern in which “higher” or “lower” parameter values consistently produced better outcomes. Instead, the results suggested condition-dependent combined patterns across the tested lighting combinations. As shown in Figures 6–8, under moderate ambient illuminance, different combinations of exhibit illuminance and correlated color temperature were associated with more stable visual responses. In contrast, under overly high ambient illuminance, insufficient exhibit illuminance was more likely to weaken the visual hierarchy between exhibits and the environment, thereby affecting viewing stability and perceived comfort. This indicates that, under the tested virtual-scene conditions, improving the light environment in history museum exhibition spaces was not associated with changing a single parameter alone, but rather with the coordinated consideration of ambient illuminance, exhibit illuminance, and correlated color temperature.

The ANOVA results are shown in Table 4. This result suggests that the duration of a single fixation remained generally stable and did not fluctuate markedly with changes in the light environment. Therefore, in this study, AFT served more as an auxiliary reference indicator rather than a core basis for judging the relative merits of different lighting conditions.

For eye-tracking indicators with significant condition effects, Bonferroni-corrected pairwise comparisons were further conducted to identify the specific differences among the 12 lighting conditions. Post hoc comparisons were conducted for TDOF, NOF, and APD, whereas AFT was not included because its overall condition effect was not significant. To keep the Results section concise, only statistically significant Bonferroni-corrected pairwise comparisons are reported in Table 5. The results showed that significant differences in TDOF were observed between C01 and C11 and between C04 and C11. For NOF, a significant difference was observed only between C01 and C12. APD showed more extensive pairwise differences, indicating that pupil response was more sensitive to changes in lighting conditions.

**Table 5.** Bonferroni-corrected pairwise comparisons for significant eye-tracking indicators.

| Indicator | Comparison | Mean Difference | Adjusted <i>p</i> | Result    |
|-----------|------------|-----------------|-------------------|-----------|
| TDOF      | C01–C11    | 1789.831        | 0.043             | C01 > C11 |
| TDOF      | C04–C11    | 1711.017        | 0.034             | C04 > C11 |
| NOF       | C01–C12    | 8.759           | 0.046             | C01 > C12 |
| APD       | C04–C07    | −0.241          | <0.001            | C04 < C07 |
| APD       | C07–C10    | 0.256           | <0.001            | C07 > C10 |
| APD       | C01–C04    | 0.255           | 0.004             | C01 > C04 |
| APD       | C07–C12    | 0.232           | 0.004             | C07 > C12 |
| APD       | C01–C10    | 0.270           | 0.008             | C01 > C10 |
| APD       | C02–C04    | 0.178           | 0.010             | C02 > C04 |
| APD       | C03–C04    | 0.167           | 0.012             | C03 > C04 |
| APD       | C02–C10    | 0.193           | 0.037             | C02 > C10 |
| APD       | C08–C10    | 0.214           | 0.043             | C08 > C10 |
| APD       | C04–C08    | −0.200          | 0.047             | C04 < C08 |

### 3.2. Analysis of Heatmaps Under Different Lighting Conditions

To further visualize the distribution characteristics of viewers' visual attention under different lighting conditions, heatmaps were generated for the 12 scenes. Since all scenes used the same exhibition interface layout, the interpretation focused on common display elements with consistent spatial positions, including the title panel, explanatory text area, right-side map, and bottom exhibit area (Figures 9–11). Overall, the main visual hotspots were concentrated around title and human image on the left, the explanatory panel and narrative text in the middle, the map on the right, and the physical exhibits at the bottom. Differences among conditions were mainly reflected in whether the hotspots could consistently stably cover the core exhibits, whether a continuous chain of attention was formed, and whether ineffective dispersion toward background or marginal areas occurred.

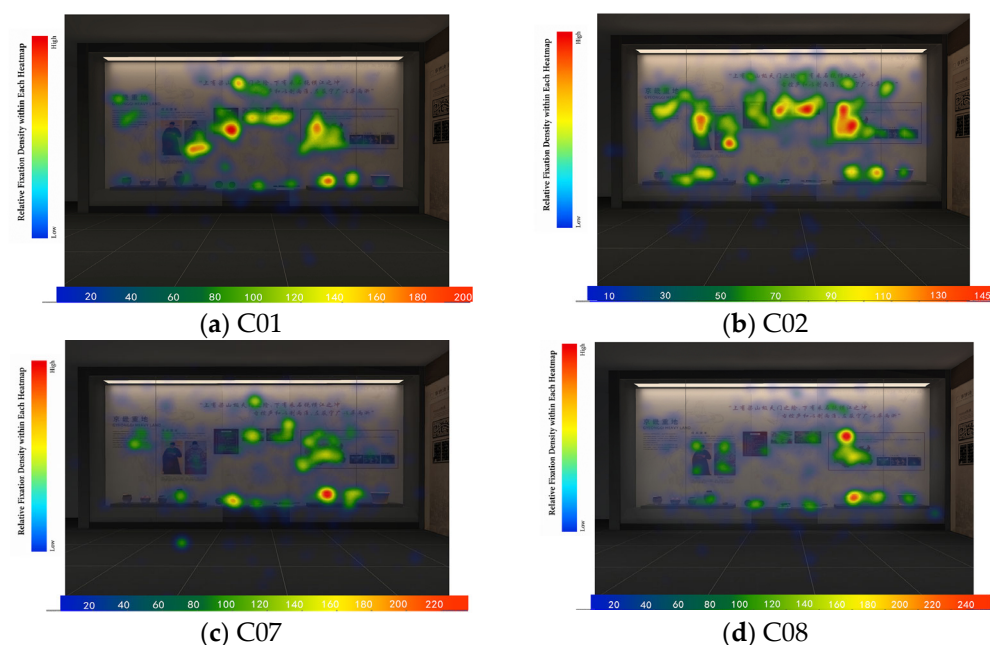


**Figure 9.** Heat maps under low overall illuminance conditions (100 lx). (a) C01; (b) C02; (c) C07; (d) C08. The Chinese text in the images is part of the simulated historical exhibition content.

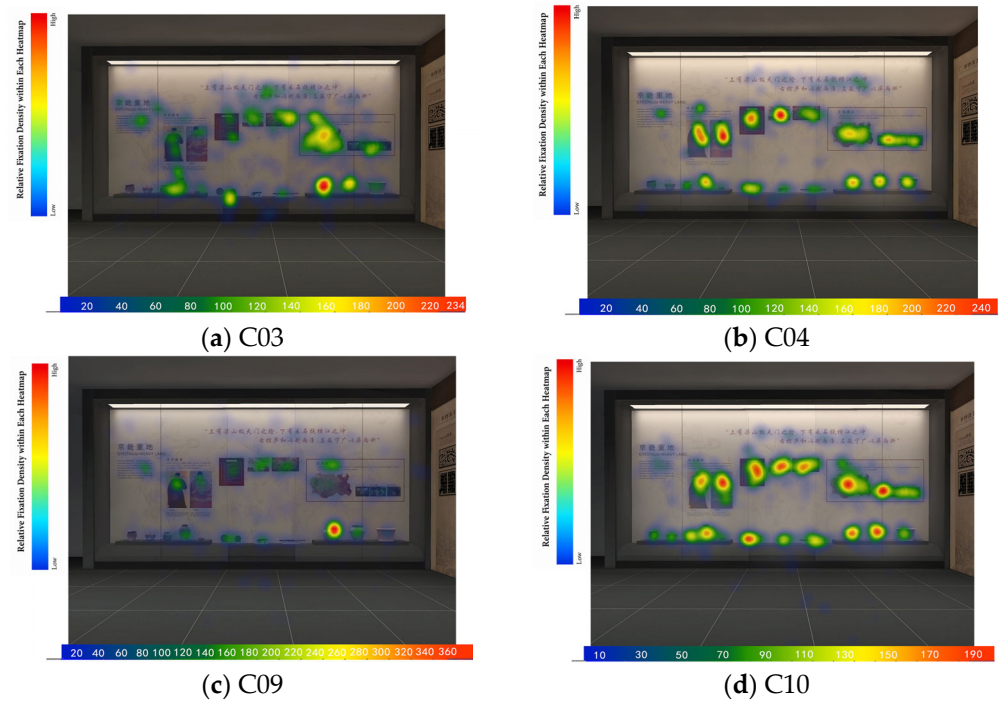


**Figure 10.** Heat maps under medium overall illuminance conditions (200 lx). (a) C03; (b) C04; (c) C09; (d) C10. The Chinese text in the images is part of the simulated historical exhibition content.

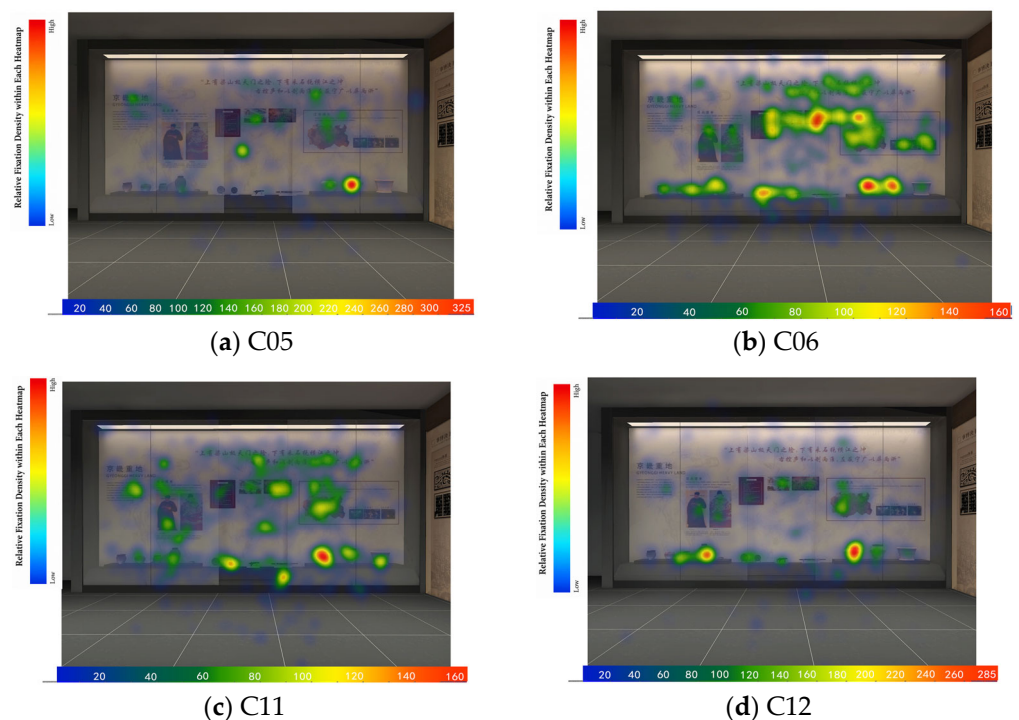


**Figure 11.** Heat maps under high overall illuminance conditions (300 lx). (a) C05; (b) C06; (c) C11; (d) C12. The Chinese text in the images is part of the simulated historical exhibition content.

When ambient illuminance was low (100 lx), the heatmaps showed obvious local focus but insufficient continuity (Figure 9). Under these conditions, viewers' attention was concentrated mainly on a few salient regions, with weak connections among hotspots and relatively limited coverage of the central explanatory information and upper narrative text. Under low ambient illuminance, when exhibit illuminance increased from 50 lx to 100 lx, the attractiveness of local exhibits was enhanced to some extent, but the hotspots remained

mainly locally clustered, and the overall browsing path was still unclear. This suggests that lower environmental brightness limits viewers' continuous perception of the entire exhibition wall.

When ambient illuminance was at a moderate level (200 lx), the heatmaps were the most stable. When exhibit illuminance was low (50 lx) (Figure 10), the hotspots could already cover the left-side figure, the right-side map, and some exhibits at the bottom, but the overall attention pattern still tended to be centered on several local areas, and the connections among exhibits remained weak. However, when exhibit illuminance was increased to 100 lx, the overlap between hotspots and core exhibits improved significantly. The central explanatory panel, the right-side map, the key exhibits at the bottom, and the narrative information above all received more continuous attention, forming a clearer band-like or serial distribution. This suggests that under moderate ambient illuminance, increasing exhibit illuminance can strengthen the visual salience of exhibits and help viewers form more stable browsing paths around the exhibition logic.

When ambient illuminance was high (300 lx), the heatmaps were more likely to show hotspot dispersion or displacement (Figure 11). If exhibit illuminance remained low (50 lx), viewers still focused on local key exhibits, but highly attended areas were more dispersed, and some attention extended to the background, blank areas, or non-key locations. The brightness hierarchy between exhibits and the background was weakened. Under such conditions, the heatmaps often lacked a clear visual center, indicating that when environmental brightness is strong, but the emphasis is insufficient, viewers are more likely to engage in ineffective searching. In contrast, when exhibit illuminance was increased to 100 lx, the attractiveness of local key exhibits recovered to some extent, and the hotspot distribution became more concentrated than in the previous condition. However, overall continuity and hierarchical clarity remained inferior to those under moderate ambient illuminance.

From the perspective of correlated color temperature, under the same illuminance combination, the positional differences between the heatmaps at 3000 K and 4000 K were less pronounced than those caused by illuminance. Correlated color temperature mainly affected hotspot aggregation strength and viewing stability, rather than fundamentally altering the areas that viewers focused on. Among the tested conditions, 200 lx ambient illuminance combined with 100 lx exhibit illuminance showed relatively good hotspot continuity and a high degree of coverage of core exhibits under both color temperature conditions, suggesting that correlated color temperature mainly plays a regulatory rather than a decisive role within the parameter range tested in this study.

Overall, the heatmap results did not show a simple pattern of "the brighter, the better", but instead visually indicated condition-dependent patterns across lighting condition combinations: under low ambient illuminance, hotspots tended to be localized; under strong ambient illuminance, hotspots were more likely to disperse; and high ambient illuminance appeared more conducive to forming a relatively stable visual center. On this basis, higher exhibit illuminance appeared to enhance the visual salience and informational continuity of core exhibits. In terms of heatmap visualization, C04 and C10 showed relatively clearer hotspot aggregation and closer overlap with exhibit areas, followed by C03 and C09, whereas C05 and C11 showed more evident background interference and attention dispersion under higher ambient illuminance and insufficient exhibit illuminance.

### 3.3. Analysis of Likert-Scale Results

To further examine viewers' subjective perceptions of exhibition spaces in history museums under different lighting conditions, this study used a Likert scale to evaluate six dimensions: perceived spatial brightness (BP), perceived warmth of the light environment

(WP), perceived spatial hierarchy (SP), perceived openness (OP), perceived safety (PS), and overall comfort (CP). First, the internal consistency of the questionnaire data was tested, and the results are shown in Table 6. The Cronbach's  $\alpha$  coefficient of the scale was 0.914, indicating high internal consistency. This result indicates that the questionnaire could reliably reflect viewers' subjective perceptions of the light environments in different scenes and could therefore be used for subsequent subjective evaluation analysis.

**Table 6.** Reliability of the Likert-scale questionnaire and overall subjective ratings across 12 scenes.

| Item                | Value             |
|---------------------|-------------------|
| Cronbach's $\alpha$ | 0.914             |
| C01                 | 2.661 $\pm$ 0.833 |
| C02                 | 3.707 $\pm$ 0.911 |
| C03                 | 4.885 $\pm$ 0.767 |
| C04                 | 5.391 $\pm$ 0.684 |
| C05                 | 5.195 $\pm$ 0.730 |
| C06                 | 5.362 $\pm$ 0.734 |
| C07                 | 2.523 $\pm$ 0.861 |
| C08                 | 3.172 $\pm$ 0.802 |
| C09                 | 4.425 $\pm$ 0.822 |
| C10                 | 5.149 $\pm$ 0.773 |
| C11                 | 4.833 $\pm$ 0.778 |
| C12                 | 5.253 $\pm$ 0.745 |

The overall mean values and standard deviations of all 12 scenes are shown in Table 6. Figure 12 presents six representative conditions selected according to the overall subjective rating results, including the three highest-rated conditions (C04, C06, and C12) and the three lowest-rated conditions (C07, C01, and C08). From the overall distribution, clear differences in subjective evaluation were found among scenes, indicating that viewers' perceptions of history museum exhibition spaces were not uniform but changed with different lighting combinations. Scenes with relatively high overall mean values were mainly concentrated in C04, C06, and C12, among which C04 had the highest overall rating, followed by C06, while C12 also maintained a relatively high level. In contrast, C07, C01, and C08 had relatively low overall ratings. This indicates that under different lighting conditions, viewers' subjective experience of the exhibition space showed a relatively clear stratification pattern, rather than increasing linearly with the increase in any single lighting parameter. In other words, scenes with higher ratings were usually not those with the strongest single lighting parameter, but rather those in which multiple parameters were relatively well coordinated.

The specific mean values of the six dimensions for each scene are shown in Table 7. Across the six dimensions, scenes with higher ratings were not completely identical across all indicators, but each had its distinct strengths. C04 performed particularly well in perceived brightness, perceived warmth, perceived openness, and perceived safety, indicating that this scene not only provided relatively clear brightness perception but also obtained more positive evaluations in terms of overall atmosphere and spatial experience. C06 showed a clearer advantage in perceived spatial hierarchy, while also maintaining relatively high levels on the other dimensions, suggesting that this scene made it easier for viewers to form a clear perception of exhibit hierarchy. Although C05 and C12 did not necessarily rank highest on every single dimension, their scores across dimensions were relatively balanced, especially in perceived comfort, indicating that these scenes were more likely to produce a stable and coordinated overall experience. In contrast, C07 and C01 generally received lower scores across multiple dimensions, particularly in perceived

brightness, perceived spatial hierarchy, and perceived comfort, indicating that these scenes were less likely to create a visually satisfying exhibition environment.

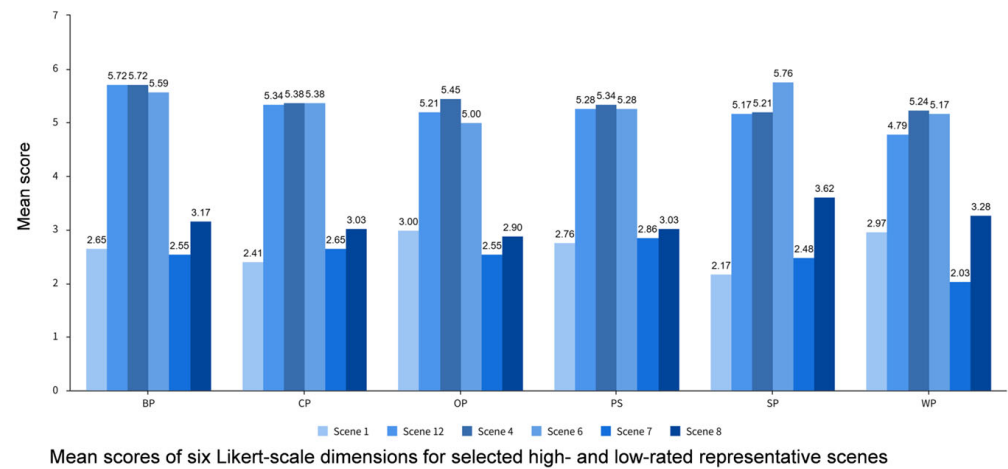


**Figure 12.** Mean scores of six Likert-scale dimensions for selected high- and low-rated representative scenes. Abbreviations: BP, brightness perception; CP, comfort perception; OP, openness perception; PS, perceived safety; SP, spatial hierarchy perception; WP, warmth perception.

**Table 7.** Mean scores of six Likert-scale dimensions across 12 scenes.

| Scene    | Brightness Perception | Warmth Perception | Spatial Hierarchy Perception | Openness Perception | Perceived Safety | Comfort Perception | Overall Mean |
|----------|-----------------------|-------------------|------------------------------|---------------------|------------------|--------------------|--------------|
| Scene 1  | 2.655                 | 2.966             | 2.172                        | 3                   | 2.759            | 2.414              | 2.661        |
| Scene 2  | 3.31                  | 4.207             | 4.103                        | 3.586               | 3.379            | 3.655              | 3.707        |
| Scene 3  | 4.655                 | 4.828             | 4.931                        | 4.966               | 4.966            | 4.966              | 4.885        |
| Scene 4  | 5.724                 | 5.241             | 5.207                        | 5.448               | 5.345            | 5.379              | 5.391        |
| Scene 5  | 5.655                 | 4.897             | 5.207                        | 5.207               | 4.793            | 5.414              | 5.195        |
| Scene 6  | 5.586                 | 5.172             | 5.759                        | 5                   | 5.276            | 5.379              | 5.362        |
| Scene 7  | 2.552                 | 2.034             | 2.483                        | 2.552               | 2.862            | 2.655              | 2.523        |
| Scene 8  | 3.172                 | 3.276             | 3.621                        | 2.897               | 3.034            | 3.034              | 3.172        |
| Scene 9  | 4.31                  | 3.931             | 4.552                        | 4.69                | 4.517            | 4.552              | 4.425        |
| Scene 10 | 5.655                 | 5.069             | 5.103                        | 5.069               | 5                | 5                  | 5.149        |
| Scene 11 | 5.103                 | 4.586             | 4.759                        | 4.621               | 5.034            | 4.897              | 4.833        |
| Scene 12 | 5.724                 | 4.793             | 5.172                        | 5.207               | 5.276            | 5.345              | 5.253        |

Further examination of Figure 12 and Table 7 shows that scenes with relatively high subjective ratings usually shared two common characteristics. First, scores across multiple dimensions were relatively balanced, rather than being exceptionally high in only one dimension. Second, there was relatively good coordination among perceived brightness, perceived hierarchy, and overall comfort. In contrast, scenes with lower overall ratings often scored low simultaneously on multiple dimensions. This suggests that viewers' subjective judgments of the exhibition light environment depend not only on brightness and color temperature, but also on whether brightness, hierarchy, spatial perception, and comfort are coordinated with one another. It also indicates that subjective experience in history museum exhibition spaces is essentially a comprehensive perceptual result, and improvement in a single dimension alone is insufficient to ensure an improvement in the overall evaluation.

Overall, the Likert-scale results indicate that different lighting conditions significantly affect viewers' subjective perceptions of exhibition spaces in history museums, particularly in terms of perceived spatial brightness, hierarchy, openness, safety, and overall comfort. Scenes with higher subjective ratings usually showed relatively balanced performance

across multiple dimensions, rather than extreme superiority in a few indicators, whereas scenes with lower ratings were more likely to show imbalance across multiple dimensions. These results provide a subjective basis for further discussion of the formation mechanism of visual comfort and perceptual preference under different lighting conditions in combination with eye-tracking indicators and heatmap results.

To further examine whether the subjective evaluation indicators differed significantly across the 12 lighting conditions, Friedman omnibus tests were conducted for the composite score and the six Likert-scale dimensions. Kendall's  $W$  was reported as the effect size. The statistical outcomes are summarized in Table 8. Significant differences across lighting conditions were found for all subjective evaluation indicators, indicating that the descriptive trends reported in Tables 6 and 7 were supported by inferential statistics. In terms of effect size, Kendall's  $W$  ranged from 0.415 to 0.627, indicating moderate-to-large differences across lighting conditions. The strongest effects were observed for the composite score ( $W = 0.627$ ) and brightness perception ( $W = 0.570$ ), whereas openness perception showed the smallest effect size ( $W = 0.415$ ). This suggests that lighting conditions had a more pronounced influence on overall evaluation and brightness-related perception than on openness perception.

**Table 8.** Omnibus tests for subjective evaluation indicators across 12 lighting conditions.

| Subjective Indicator              | $\chi^2$ | df | $p$    | Kendall's $W$ |
|-----------------------------------|----------|----|--------|---------------|
| Composite score                   | 200.047  | 11 | <0.001 | 0.627         |
| Brightness perception (BP)        | 181.730  | 11 | <0.001 | 0.570         |
| Warmth perception (WP)            | 138.357  | 11 | <0.001 | 0.434         |
| Spatial hierarchy perception (SP) | 150.296  | 11 | <0.001 | 0.471         |
| Openness perception (OP)          | 132.341  | 11 | <0.001 | 0.415         |
| Perceived safety (PS)             | 138.116  | 11 | <0.001 | 0.433         |
| Comfort perception (CP)           | 154.021  | 11 | <0.001 | 0.483         |

### 3.4. Integrated Analysis of Subjective and Objective Results

To more clearly present more intuitively the changing trends of representative subjective and objective indicators under different ambient illuminance conditions, this study selected overall mean value, comfort perception, average pupil diameter (APD), and total duration of fixation for trend fitting analysis. APD was included as an auxiliary physiological indicator related to relative visual stimulus strength. As shown in Figure 13, the fitted curves were used to visualize the variation trends of selected subjective and objective indicators with ambient illuminance. The composite score and visual comfort showed clearer increasing-then-stabilizing trends, with adjusted  $R^2$  values of 0.68 and 0.56, respectively. By contrast, the fitted trend for total fixation duration was weak, with an adjusted  $R^2$  value of  $-0.02$ . Therefore, the trend fitting was mainly used to describe possible visual patterns, while the interpretation of lighting effects was based on the combined evidence from descriptive statistics, omnibus tests, correlation analysis, and heatmap results.

To further test the correspondence between objective eye-tracking indicators and subjective evaluation results, Pearson correlation analysis was conducted between the main eye-tracking indicators and the subjective evaluation dimensions. The results are shown in Figure 14. Overall, perceived brightness, perceived spatial hierarchy, perceived safety, perceived comfort, and the overall mean score showed strong positive correlations with one another, indicating a high degree of consistency among different subjective evaluation dimensions. In contrast, the reverse-coded APD showed positive correlations with several subjective dimensions. However, because APD is strongly affected by retinal luminance flux, this relationship should be interpreted as an auxiliary physiological correspondence rather than as direct evidence of visual comfort. Total duration of fixation and number of

fixations showed moderate negative correlations with subjective dimensions. These results indicate that subjective evaluations and objective eye-tracking indicators showed partially consistent changing trends, but APD-related results were interpreted together with fixation indicators and subjective evaluations rather than as independent evidence of comfort.

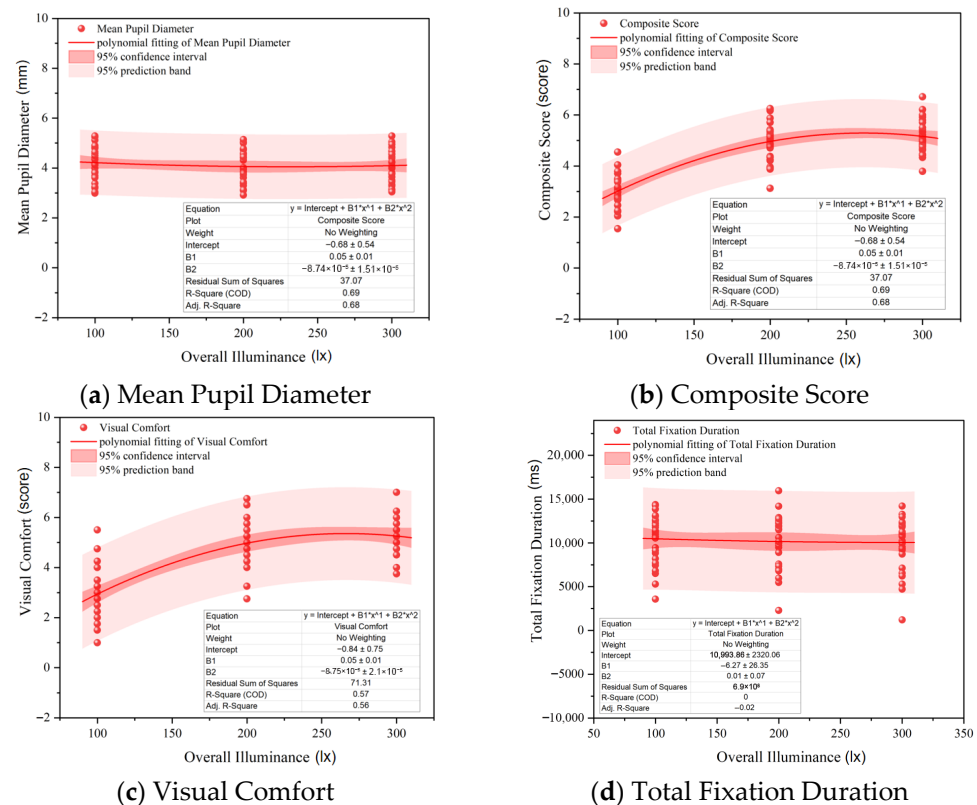


Figure 13. Regression Curves of Subjective and Objective Indicators.

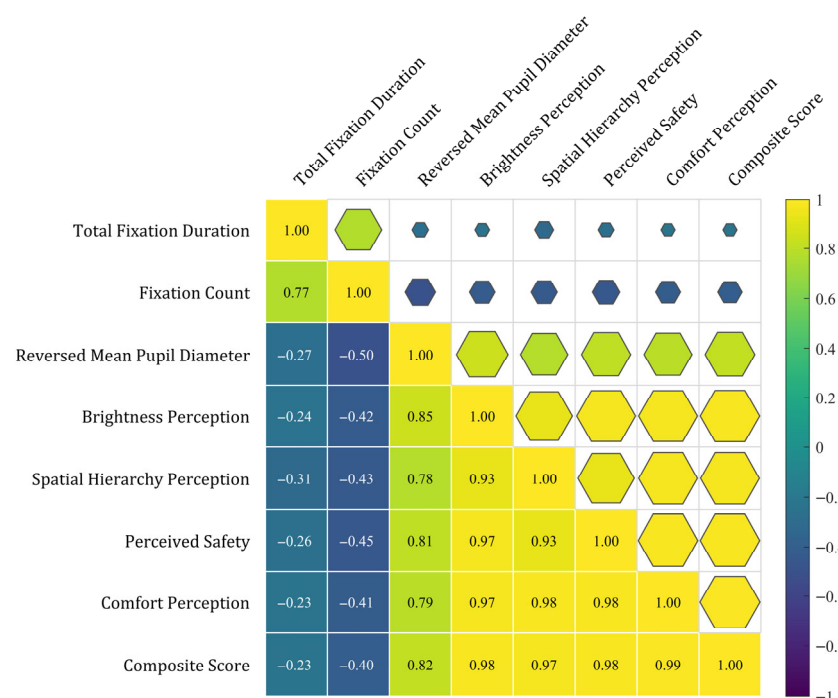


Figure 14. Correlation matrix of eye-movement indicators and subjective ratings.

## 4. Discussion

### 4.1. Effects of Light Environment Parameters on Exhibition Perception in History Museums

The combined subjective evaluation and eye-tracking results indicate that viewing performance varied across the tested lighting conditions composed of different ambient illuminance, exhibit illuminance, and correlated color temperature settings. Among these, ambient illuminance determines environmental legibility and the intensity of background competition; exhibit illuminance determines the prominence of key information; and correlated color temperature mainly affects spatial atmosphere and interface perception.

Ambient illuminance is the fundamental variable affecting the viewing organization. When ambient illuminance is low, viewers' attention tends to concentrate more easily on locally salient areas, but coverage of explanatory information and surrounding content becomes insufficient, resulting in weak viewing continuity. When ambient illuminance is high, the visibility of background areas increases and perceived brightness improves, but the brightness difference between key exhibits and the background is reduced, making attention more likely to disperse. By contrast, moderate ambient illuminance is more conducive to maintaining both environmental recognizability and background control, thereby forming more stable viewing paths.

Exhibit illuminance mainly affects the visual priority of core exhibits. Lower exhibit illuminance can meet basic visibility requirements, but the recognition advantage of key content remains unclear. When exhibit illuminance is increased, the overlap between hotspot distribution and key exhibits and explanatory information becomes more evident, indicating that accent lighting may strengthen the salience of exhibits and improve information continuity during the viewing process. Therefore, the role of exhibit illuminance lies not simply in making exhibits brighter, but in establishing a hierarchical relationship between exhibits and the background.

The effect of correlated color temperature on viewing organization is weaker than that of illuminance, but it changes the direction of spatial perception. Under the 3000 K condition, the space is more likely to produce a relatively stable and gentle viewing atmosphere. Under the 4000 K condition, interface clarity and information recognizability become stronger. Both can be used in history museum exhibition spaces, but the former is more suitable for emphasizing atmosphere control, whereas the latter is more suitable for emphasizing information expression. Therefore, correlated color temperature is more appropriate as a supplementary atmospheric parameter used in coordination with illuminance parameters, rather than as an independent basis for optimization.

Under the tested virtual-scene conditions, more favorable perceptual responses were mainly observed under the following combination: moderate ambient illuminance as the environmental base, relatively high exhibit illuminance to emphasize key exhibits, and correlated color temperature regulated within the range of 3000–4000 K. This result should be interpreted as a relative pattern observed in the present controlled experiment rather than as a directly applicable lighting standard for real museum spaces. To further summarize the preliminary parameter intervals observed in this study, a schematic diagram of parameter intervals was drawn, as shown in Figure 15.

### 4.2. Preliminary Design Implications Under the Tested Virtual-Scene Conditions

Based on the parameter patterns identified above, the experimental results may provide preliminary implications for light-environment organization in different functional zones of history museum exhibition spaces. These implications should be understood as hypothesis-generating references that require further field validation. Compared with single-parameter optimization, zonal configuration better reflects the differences in viewing tasks during the actual visiting process. According to the basic visiting sequence of

static exhibition spaces, these spaces can be divided into the entrance introduction zone, transition buffer zone, core exhibition zone, and exit zone, and a general design-strategy bubble diagram was formed accordingly, as shown in Figure 16.

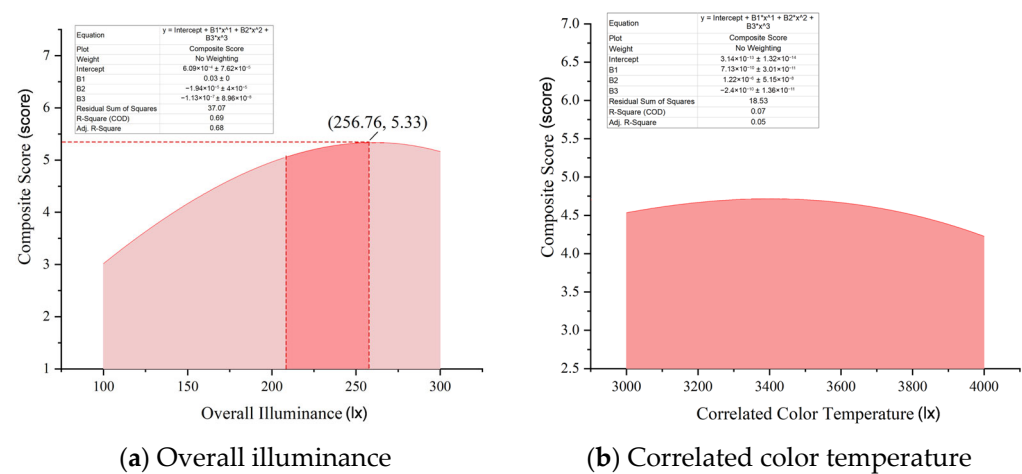


Figure 15. Preferred ranges of key lighting parameters under the tested virtual-scene conditions.

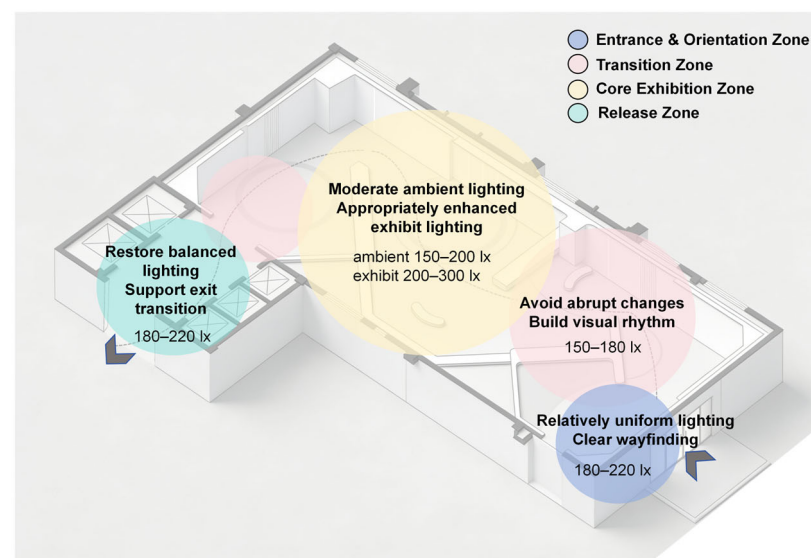


Figure 16. Zonal design strategies for exhibition spaces in history museums. The dashed lines indicate the boundaries between different functional zones.

The entrance introduction zone mainly supports visual adaptation and wayfinding recognition. Lighting in this zone should maintain relative uniformity to avoid abrupt brightness contrast after visitors enter the exhibition hall. Based on the tested virtual-scene conditions, an illuminance range of 180–220 lx may be considered as a preliminary reference for supporting basic visibility, wayfinding clarity, and visual adaptation.

The transition buffer zone mainly facilitates the shift from introduction to focused viewing. This zone should not form a new high-brightness center, but should maintain visual continuity through relatively gentle changes in brightness. Based on the tested virtual-scene conditions, an illuminance range of 150–180 lx may be considered as a preliminary reference for reducing abrupt brightness changes and reserving hierarchical contrast for the core exhibition zone.

The core exhibition zone is the area where artifact display and information acquisition are most concentrated. Special attention should therefore be paid to the relationship

between ambient illuminance and exhibit illuminance. This zone is suitable for a lighting strategy that combines moderate ambient illuminance with enhanced exhibit lighting. Specifically, under the tested virtual-scene conditions, ambient illuminance of 150–200 lx and exhibit illuminance of 200–300 lx may be considered as preliminary reference ranges for enhancing the recognizability of key exhibits and viewing continuity; however, exhibit illuminance should be further adjusted according to artifact conservation requirements, especially for light-sensitive materials such as textiles, pigmented paper, and organic dyes. Correlated color temperature may be adjusted within the range of 3000–4000 K according to the exhibition theme, but it should not replace the dominant role of illuminance hierarchy.

The role of the exit zone shifts from focused viewing to departure guidance. The lighting organization in the exit zone should gradually return from contrast control to a more balanced state. Based on the tested virtual-scene conditions, an illuminance range of 180–220 lx may be considered as a preliminary reference for supporting directional recognition and departure transition.

In summary, the light environment design of history museum exhibition spaces should be configured according to the viewing tasks of different functional zones rather than using uniform parameters throughout the whole space. The entrance introduction zone emphasizes uniformity and recognition, the transition buffer zone emphasizes continuity and gradual change, the core exhibition zone emphasizes hierarchy and focus, and the exit zone emphasizes visual recovery and transition. This zonal strategy may provide a preliminary reference for future field-based validation and light-environment organization in static exhibition spaces.

## 5. Conclusions

### 5.1. Research Findings

The main findings of this study are as follows:

Different lighting conditions resulted in significant differences in visual attention and subjective perception. Specifically, lighting conditions formed by different combinations of ambient illuminance, exhibit illuminance, and correlated color temperature produced distinct viewing responses. Lower ambient illuminance tends to produce localized but discontinuous attention distribution, whereas higher ambient illuminance is more likely to strengthen background competition and weaken the visual hierarchy between exhibits and the environment. By contrast, moderate ambient illuminance provides a more stable basis for viewing. Under the tested virtual-scene conditions, this indicates that improving perceived lighting quality was not associated simply with increasing brightness, but with establishing a relative balance between environmental legibility and exhibit prominence.

Exhibit illuminance is a key parameter for strengthening exhibit salience and improving viewing continuity. When exhibit illuminance was increased from 50 lx to 100 lx, the overlap between hotspots and explanatory panels, maps, and key exhibits became more evident, and viewers were more likely to form continuous browsing paths around the exhibition logic. This indicates that increasing exhibit illuminance is meaningful not merely because it makes the exhibits brighter, but because it helps establish a clearer visual priority order. In this study, the combination of 200 lx ambient illuminance and 100 lx exhibit illuminance showed relatively good stability in both subjective and objective results.

Correlated color temperature showed a relatively secondary influence compared with illuminance distribution within the tested conditions. Within the parameter range tested in this study, 3000 K and 4000 K did not fundamentally alter the main areas of visual focus, but they did affect viewing stability and the perception of spatial atmosphere. Compared with the illuminance hierarchy, correlated color temperature had a weaker direct effect on the distribution of visual attention, but a more evident influence on spatial atmosphere

and perceptual tone. Therefore, in history museum exhibition spaces, correlated color temperature should be interpreted as an atmosphere-adjustment parameter after a reasonable illuminance hierarchy has been established, rather than as the sole basis for optimization.

### *5.2. Design Strategies for the Light Environment of History Museum Exhibition Spaces*

Based on the above conclusions, this study proposes the following light environment design strategies:

A lighting structure centered on the hierarchical difference between exhibits and background may be considered in future museum lighting design. History museum exhibition spaces should be neither too dark nor excessively bright overall. Ambient illuminance should be controlled within a moderate range to ensure the basic legibility of the exhibition environment. At the same time, exhibit illuminance should be clearly higher than background illuminance so that core exhibits and key information zones can become stable visual centers.

Visual guidance should be strengthened primarily through exhibit illuminance rather than by simply increasing ambient brightness. For static historical exhibitions, lighting design should help viewers quickly identify major exhibits and form continuous viewing paths. Therefore, compared with simply increasing ambient illuminance, a more effective approach is to increase exhibit illuminance on the basis of a reasonable environmental brightness level, especially for explanatory panels, maps, and key cultural relics that serve important narrative functions.

Correlated color temperature should be used as a parameter for atmosphere coordination rather than as a substitute for illuminance design. On the basis of a reasonable illuminance hierarchy, correlated color temperature may be adjusted within the tested range of 3000–4000 K according to the exhibition theme and spatial narrative requirements, so as to balance historical atmosphere and information legibility. Its role is more suitable for regulating spatial character than for being independently optimized apart from the illuminance structure.

### *5.3. Research Limitations and Prospects*

This study has several limitations. First, the experimental scene was constructed on the basis of a unified historical static exhibition interface and did not cover light environment differences under varying exhibition hall scales, different exhibit types, and more complex display media conditions. Second, this study included only two correlated color temperature levels, 3000 K and 4000 K, together with a limited number of ambient illuminance and exhibit illuminance combinations, which was insufficient to reveal threshold characteristics under more refined parameter intervals. Therefore, the tested CCT range should not be interpreted as an optimal or preferred range beyond the present experimental conditions. Third, the sample size for subjective evaluation was relatively limited. Accordingly, the subjective evaluation results should be interpreted as supporting evidence within this experiment. Future research may further expand the sample size, enrich exhibition types and parameter levels, and combine more refined behavioral data and statistical models to conduct more detailed verification of the optimization mechanism of the light environment in history museum exhibition spaces.

A further limitation concerns the use of monitor-based virtual scenes. Although this approach allowed the three lighting parameters to be controlled and compared systematically, it cannot fully reproduce the perceptual complexity of real museum spaces. In actual exhibition environments, spatial scale, high-dynamic-range (HDR) luminance distributions, surface reflectance, glare, embodied visitor movement, in situ visual adaptation, daylight–electric light interaction, and material texture may all influence visual comfort

and perceptual preference. Therefore, the findings of this study should be interpreted as relative perceptual evidence under controlled virtual-scene conditions rather than as direct lighting prescriptions for real museum spaces. Future studies should further validate these results through physical mock-up experiments, on-site illuminance and luminance measurements, and field experiments in actual museum environments.

Another limitation concerns the interpretation of APD. APD is directly influenced by retinal luminance flux; therefore, in this study, APD should be interpreted as an auxiliary photophysiological indicator of relative stimulus strength rather than as direct evidence of visual comfort or cognitive load. In addition, the actual photometric output of the monitor across the 12 rendered scenes was not measured. Future studies should measure screen luminance and retinal illuminance more precisely to distinguish pupil light-reflex responses from perceptual judgments.

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**Institutional Review Board Statement:** This study involved non-invasive eye-tracking recording and questionnaire responses from adult volunteers. Formal ethical review was waived because the study was non-medical, non-interventional, and minimal-risk, and all eye-tracking and questionnaire data were anonymized and used solely for academic research. According to Article 32 of the Measures for Ethical Review of Life Science and Medical Research Involving Humans issued by the National Health Commission, Ministry of Education, Ministry of Science and Technology, and National Administration of Traditional Chinese Medicine of China, ethical review may be exempted for research using anonymized human information data, provided that the study causes no harm to the human body and does not involve sensitive personal information or commercial interests. The study did not involve clinical intervention, treatment, biological samples, vulnerable groups, personally identifiable information, sensitive private data, or commercial interests.

**Informed Consent Statement:** Written informed consent was obtained from all participants. Before the experiment, participants were informed of the study's purpose, experimental procedure, data use, anonymization procedure, and their right to withdraw at any time.

**Data Availability Statement:** The data presented in this study are only available on request from the corresponding author due to privacy concerns.

**Conflicts of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

## Abbreviations

The following abbreviations are used in this manuscript:

| Abbreviation | Full Term                    |
|--------------|------------------------------|
| APD          | Average Pupil Diameter       |
| AFT          | Average Fixation Time        |
| BP           | Brightness Perception        |
| CCT          | Correlated Color Temperature |
| CP           | Comfort Perception           |
| NOF          | Number of Fixations          |
| OP           | Openness Perception          |

|      |                              |
|------|------------------------------|
| PS   | Perceived Safety             |
| SP   | Spatial Hierarchy Perception |
| TDOF | Total Duration of Fixation   |
| WP   | Warmth Perception            |

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