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Status of Typical Artificial Lighting Environments in Different Public Buildings in China, and Requirements for Their Improvement

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Abstract: The luminous environment is an essential factor that affects people's working and living experiences in buildings. In order to clarify the building luminous environment parameters that are required for occupant satisfaction, we collected 2553 completed questionnaires while conducting field measurements of new and updated luminous comfort metrics in 15 contexts in four cities in China. By developing a five-step approach to identifying the luminous environment needs of different building occupants, including data cleaning, correlation analysis, and nonparametric testing, we determined the thresholds for all key metrics for each scenario. The research results show that different public building environments have unique luminous environment improvement requirements, and this conclusion can guide future lighting design, LED technology and daylighting integration technology.

Keywords: interior lighting; public buildings; key factors; satisfactory thresholds; luminous comfort

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1. Introduction

1.1. Luminous Environment

Architectural lighting is an essential part of public building environment creation because light affects human health and wellbeing [1–4], as well as luminous comfort [5,6] to various degrees. In public buildings like offices, markets, and roads, luminous comfort has always been a critical factor in designing appropriate lighting conditions [7–9]. However, different public buildings have unique luminous requirements. For instance, 500 lx is recommended for deskwork in classrooms, whereas 100–300 lx is suitable for computer work in offices [10,11]. Therefore, to improve luminous comfort, it is crucial to consider the specific lighting demands of each context and adjust the factors of the luminous environment accordingly.

1.2. Luminous Comfort

Luminous comfort is a crucial aspect of achieving high-performance building design. However, defining luminous comfort, particularly under artificial lighting, remains a challenge due to a lack of standardization. The most widely accepted approach to defining luminous comfort is the "NON-annoyance approach", which assumes that "comfort is not discomfort" [12,13]. In fact, it is easier to evaluate discomfort quantitatively and qualitatively than comfort, which lacks a clear definition [14,15]. Studies on artificial lighting comfort testing primarily fall into two categories. The first type is laboratory-based, where rooms are equipped with shading devices to eliminate the influence of daylighting [8,16,17]. The other is a study of the luminous environment at night, including surveys [18,19]. Currently, evaluating the comfort of the luminous environment mainly relies on occupant experiences regarding the quantity and quality of light in a specific context. Some researchers have measured this comfort level in terms of occupant satisfaction with their perceptual experiences. However, it has been noted that satisfaction with the luminous environment can be influenced by various factors, including physical environmental parameters. In this study, "luminous comfort" is defined as occupant satisfaction with the luminous environment created by artificial lighting [20,21].

Individual differences in luminous comfort can significantly affect how satisfactory occupants perceive the luminous environment to be [22,23]. Therefore, there is currently no consensus on which factors can accurately predict luminous comfort. To better understand the relationship between factor assessments and occupant evaluations, it is necessary to conduct extensive fieldwork [24,25]. The major factors affecting occupant comfort include illuminance and correlated color temperature (CCT) in the luminous environment [26–28]. However, the preferred illuminance level varies significantly depending on the context [29,30], and some researchers have suggested using different CCTs for working and relaxation purposes. Occupant evaluations have also led to the proposal of metrics for evaluating luminous comfort, such as percent flicker and the flicker index [31,32]. Flicker is a primary cause of luminous discomfort in public buildings, it can occur as an impression of unsteadiness of visual perception induced by a light stimulus whose luminance or spectral distribution fluctuates with time [33,34]. The flicker index (PI), which measures the ratio of the difference between the maximum and minimum light output of a light source to the sum of the maximum and minimum light output, is an important factor for assessing flicker. Moreover, there is a significant correlation between occupant satisfaction and luminance distribution [35]. Correlations have been found between the brightness of indoor surfaces and occupants' visual experiences of a space. For example, increasing the illuminance of walls can make a room more visually stimulating [36] and also enhance the acceptability and comfort of brightness [37]. High brightness perception has been associated with increased comfort and spaciousness evaluation [31]. Moreover, the image-forming pathway or its interaction with the non-image forming pathway can affect physiological factors and mood [38,39]. Recently, an increasing number of metrics have been proposed to quantify non-visual effects based on current findings, which have been strongly related to comfort [40–42]. As a result, the number of evaluation dimensions for luminous environments is expanding, and new factors are being identified [43]. Therefore, future studies on lighting design must consider these newly proposed metrics to better understand occupant needs and create luminous environments that promote well-being.

1.3. Evaluation of Luminous Comfort

As science and technology continue to advance, new luminous factors are emerging, and evaluation methods for the luminous environment are also improving. Earlier evaluations focused on objective factors such as illuminance, brightness, and CCT [44,45]. Researchers employed one-way and multivariate analyses of variance to explore the effects of these factors on occupants' perceptions of luminous environments [46]. More recent studies have primarily relied on user questionnaires to evaluate subjective components [47]. The evaluation involves having subjects make appraisals of lighting situations (a single factor), which the experimenter then processes through a statistical analysis [48]. Flynn's research has demonstrated how environmental lighting can influence user impressions and behavior through different lighting arrangements [49]. Similarly, Kruithof et al. have investigated the impact of combinations of illuminance and CCT on occupant satisfaction, finding that high CCTs and high illuminance levels are generally preferred [50]. In addition, some researchers have focused on analyzing the relationship between objective and subjective factors through factor analysis. S Fotios et al. used regression analysis to study the correlation between luminous factors and human experience [51], while Aries employed path analysis to explore the relationship between subjective and objective factors in luminous comfort [52]. Furthermore, when examining indoor environments, Mak et al. relied on Mann–Whitney *U* tests to evaluate differences in preferences between two populations [53]. Questionnaire surveys are often considered a more comprehensive method for assessing factors affecting luminous comfort compared to factor analysis. The chosen evaluation methods play a crucial role in determining the results of the evaluation process. While subjective questionnaires may better express participants' true feelings, parametric analysis can provide a more accurate representation of the current state of public buildings [54]. However, there is currently no consensus in the scientific literature regarding the optimal approach for evaluating environmental factors and the intended use of a building.

1.4. Purpose of This Study

Many previous evaluation studies have been conducted on different types of public buildings using various statistical analysis methods, often with inconsistent conclusions regarding luminous environments. In order to identify the key metrics and thresholds affecting occupant comfort, this study used a large-scale simultaneous on-site measurement and questionnaire survey approach across five distinct types of public buildings. A unified five-step statistical analysis procedure was then employed to identify the critical factors and thresholds for each typical scenario. The results of this study can provide valuable guidance for creating and improving comfortable luminous environments in public buildings.

2. Methodology

In order to identify the key metrics and thresholds affecting occupant luminous comfort, this study began by conducting simultaneous on-site measurements and a questionnaire survey. A five-step statistical analysis procedure was then employed for each typical scenario, as illustrated in Figure 1. By using this methodological approach, we can better understand the complex interplay between various environmental factors and occupant experiences of luminous environments.

2.1. Questionnaire

The questionnaire used in this study included questions about personal information, prior experience with luminous environments, and overall environmental satisfaction, as well as physical and psychological questions. All questions were rated on a five-point Likert scale, where 1 represented "very dissatisfied" and 5 represented "very satisfied". Items related to experiences with luminous environments focused on perceptions of each factor, such as illuminance (vertical and horizontal), luminance contrast, space brightness, CCT, color rendering index (CRI), and flicker. To reduce potential bias in responses, a large number of questionnaires were collected to ensure robust conclusions. Questionnaire items and rating scales were kept simple and consistent, with descriptions were crafted in plain language to minimize the use of technical jargon. All measurements were taken simultaneously, and the questionnaire was administered during a specific time frame from 7:00 p.m. to 9:00 p.m. under artificial lighting conditions. Taking office buildings as an example, the questionnaire used is shown in Appendix A.

2.2. Pilot Study

To ensure the reliability of the questionnaire used in the main study, a pilot study was conducted in office buildings with 100 volunteers. Responses from the pilot study were used to validate the selected statistical methods and confirm the logical and reasonable nature of the questionnaire items, as shown in Table 1.

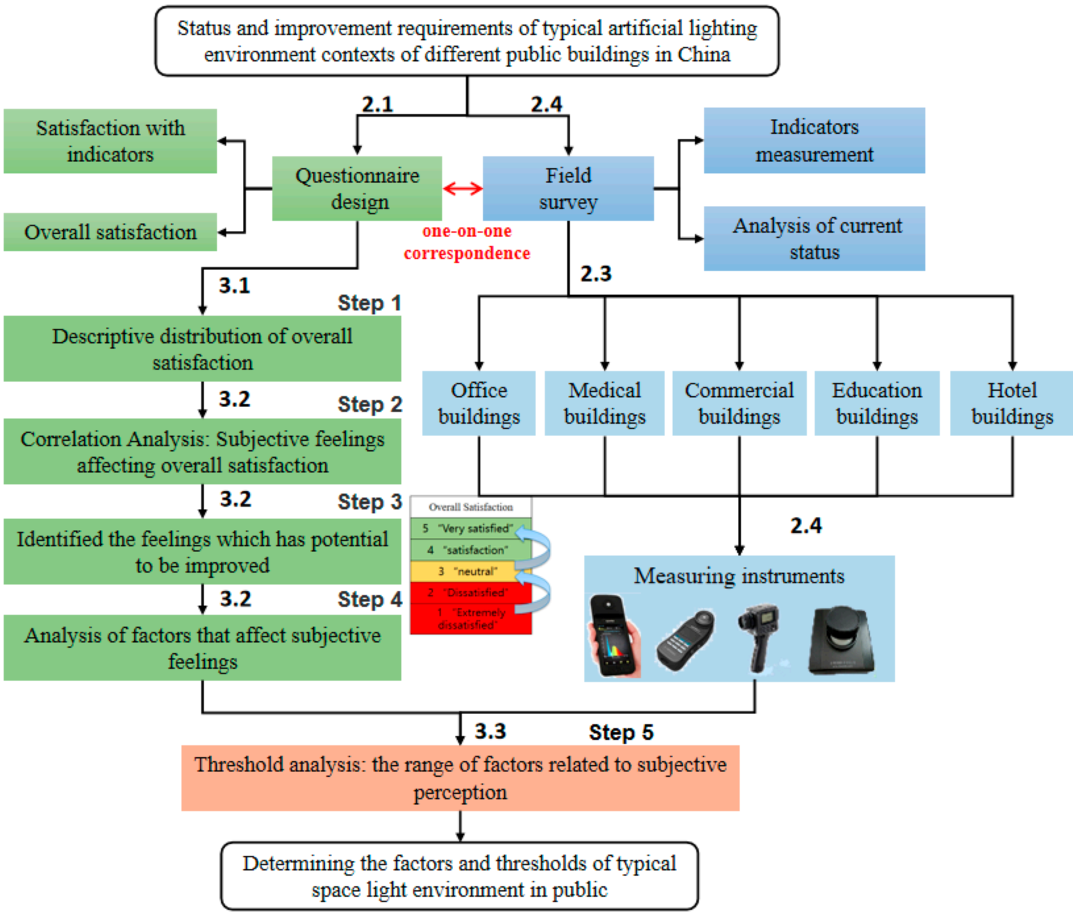

Figure 1. Analysis flowchart.

Table 1. Bartlett and KMO Test.

	KMO	Based on Standardized Cronbach Alpha Coefficient
office	0.686	0.777
conference rooms	0.791	0.777
corridors	0.628	0.746

Based on the results of the pilot study, one item in the questionnaire was modified prior to the main study.

The Kaiser–Meyer–Olkin (KMO) values for sampling adequacy were all greater than 0.6, indicating that the pilot study data were suitable for factor analysis. Additionally, the Bartlett sphere test confirmed the validity of the pilot study data. Reliability of the questionnaire items was assessed using Cronbach's α coefficient, which ranged from 0.7 to 0.8. These coefficients indicated good internal consistency and reliability of the items used in the questionnaire.

2.3. Sampling

This study focused on assessing luminous comfort in public buildings, including offices, hospitals, commercial spaces, hotels, and educational facilities. A total of 15 buildings across four cities in China were evaluated, as summarized in Table 2. The selected cities are all considered to be first-tier or super-first-tier, with well-established lighting infrastructures and high standards for environmental quality. This facilitated obtaining evaluations of "very satisfied" from occupants, which was necessary for identifying important thresholds for different factors. To ensure data quality, a basic set of standards was applied during the data cleaning process to describe the status quo of the luminous environment in public buildings, calculate standard-reaching rates, and remove the data that did not meet the standard [45].

Table 2. Investigation and measurement.

Building Type	City	Context	Data Cleaning	Total	Valid	Issued	Standard-Reaching Rate
Office	Beijing Shanghai	Office	82	246	396	475	62.1%
		Conference room	86				
		Corridor	78				
Medical	Shanghai	Ward	63	168	186	249	90.3%
		Nurse station	57				
		Corridor	48				
Commercial	Beijing Shanghai	Lobby	56	166	210	261	79.0%
		Corridor	57				
		Supermarket	53				
Hotel	Nanjing Changsha	Guest room	95	237	327	384	72.5%
		Lobby	83				
		Corridor	59				
Education	Beijing	Classroom	606	606	993	1154	61.0%
Total				1423	2112	2553	67.4%

Room selection for the buildings under investigation listed in Table 2 did not have strict requirements, as the primary goal was to collect a large number of questionnaires. Rooms were selected with moderate occupant distribution to prevent disturbances during the luminous environment evaluation process.

Data for the survey were collected between November and December 2019, with volunteers recruited from the building occupants themselves. Most volunteers did not have professional experience related to lighting, and the questionnaire was designed in spoken language to facilitate easy understanding. Each volunteer completed a questionnaire in their respective context, resulting in a total of 1423 valid questionnaires collected from the same number of participants. Volunteers' demographic information is summarized in Table 3, with all participants being Chinese nationals. Collectively, these data facilitated a comprehensive evaluation of the luminous environment in various types of public buildings, enabling us to identify critical factors and thresholds that can inform future lighting design and technology development efforts.

Table 3. Descriptive statistics of volunteers' information.

Building Type	Gender		Age				
	Male	Female	18–20	20–29	30–39	40–49	50–59
Office building	174 (70.7%)	72 (29.3%)	0	156 (63.4%)	65 (26.4%)	19 (7.7%)	6 (2.4%)
Medical building	112 (66.7%)	56 (33.3%)	0	38 (22.6%)	39 (23.2%)	46 (27.4%)	45 (26.8%)
Commercial building	80 (48.2%)	86 (51.8%)	0	73 (44.0%)	51 (30.7%)	32 (19.3%)	10 (6.0%)
Hotel building	133 (56.1%)	104 (43.9%)	0	85 (35.9%)	91 (38.4%)	47 (19.8%)	14 (5.9%)
Education building	352 (66.7%)	254 (41.9%)	398 (65.7%)	208 (34.3%)	0	0	0
Total	851 (59.8%)	572 (40.2%)	398 (28.0%)	560 (39.4%)	246 (17.3%)	144 (10.1%)	75(5.3%)

A total of 1423 participants completed the questionnaire, including 851 males and 572 females, with ages ranging from 18 to 59 years (mean age 28.30, SD 9.96). Prior to the luminous environment evaluation process, volunteers were invited to complete the questionnaire voluntarily. To compensate participants for their time and effort, small gifts were provided as rewards.

2.4. On-Site Measurement

The lighting conditions in public buildings were maintained at typical daytime levels throughout the evaluation process, with stable luminaires and no changes made during the test period. There were no associated risks of exposure or ethical concerns related to the study design. To ensure comprehensive data collection, all primary indoor environmental parameters were measured and recorded while volunteers completed the questionnaires, as depicted in Figure 2. Information about the relevant measuring instruments used in the study is summarized in Table 4.

$$F_{eu} = 1.5 \times Lg^{0.7} = 1.5 \times \left(\sqrt[N]{\prod_{\theta=-50^\circ}^{35^\circ} \prod_{\theta=-50^\circ}^{50^\circ} L(\theta,\phi)} \right)^{0.7} \tag{1}$$

$$C = \frac{LT - LB}{LB} \tag{2}$$

Figure 2. Field test: (**a**) office building; (**b**) medical building; (**c**) commercial building; (**d**) education building; (**e**) hotel building.

Table 4. Measuring instruments and accuracies.

Measurement Parameters	Measuring Instrument	Measurement Accuracy
Illuminance (E)	Illuminance meter (EVERFINE Z-10)	±2%
Correlated color temperature (CCT)	Spectrometer (EVERFINE SPIC-200A)	±3%
Color rendering index (CRI)	Spectrometer (EVERFINE SPIC-200A)	±1%
Luminance (L)	Luminance meter (KONICA MINOLTA LS-160)	±4%
Percent flicker	Stroboscope (EFB-M)	±1%

According to the measured parameters in Table 4, the three important parameters that affect people's perception of the luminous environment can be obtained: space brightness index, luminance contrast and uniformity ratio of illuminance. The calculation of the spatial brightness index is shown in Formula (1), where Lg is the geometric mean of brightness, θ is the vertical field of view, –50° to 35°; ϕ is the horizontal field of view, –50° to 50°). The calculation of luminance contrast is shown in Formula (2), where LB is background luminance; LT is target luminance. And the uniformity ratio of illuminance is the ratio of minimum illuminance to average illuminance.

For each survey data point, measurements were taken at specific, fixed locations relative to the participant. The measuring points on the horizontal plane were located on the desktop surface (at a height of 0.75 m) to measure the horizontal illuminance and radiation spectrum. The measuring points on the vertical plane were located at the height of the human eye (approximately 1.2 m), where vertical illuminance and luminance were measured. According to the measured radiation spectrum data, the values of CCT and CRI could be obtained by calculation. When evaluating flicker index and percent flicker (PF), we pointed the stroboscope at the relevant luminaire. For consistency and accuracy, each parameter at each test point was measured six times, with the average value used to derive the final results.

2.5. Data Processing and Analysis

This study proposes a novel five-step method for identifying key metrics and thresholds that contribute to occupant comfort in public buildings. Firstly, a descriptive distribution of overall satisfaction was obtained through the questionnaire survey. Secondly, the Spearman rank correlation coefficient test was utilized to identify key subjective factors (e.g., spatial brightness, illuminance) that influenced participants' satisfaction with the total luminous environment. Thirdly, the Mann–Whitney *U* test revealed the differences in volunteers' key subjective perceptions between different overall satisfaction levels and identified the perceptions that had potential to be improved. Fourthly, data from both the questionnaires and measurements were encoded and analyzed using SPSS 25, and key factors that affect potential perceptions were recognized with correlation tests for each scene. Finally, according to the potential subjective perceptions, the thresholds of the key metrics were obtained for satisfaction improvement.

Together, these steps allowed us to gain a more comprehensive understanding of the complex factors that influence occupant comfort in public buildings, providing insights that can be used to inform future efforts aimed at promoting healthier and more comfortable building environments.

3. Results

3.1. Descriptive Analysis of Overall Satisfaction

The satisfaction rates for the luminous environment in different contexts are shown in Figure 3. Levels 1 and 5 accounted for less than 5% of the total responses. In order to ensure data completeness and to facilitate subsequent analysis, levels 1 and 2 were reclassified as dissatisfaction, level 3 as neutrality, and levels 4 and 5 as satisfaction.

Among the various types of public buildings studied, the highest level of satisfaction was reported in office environments, with a satisfaction rate of 65%. In contrast, satisfaction levels in conference rooms were slightly lower, at 45%, and the proportion of dissatisfaction in this context increased by 17%. Interestingly, despite having the lowest overall satisfaction rate, of 35%, the corridor did not exhibit a significant increase in dissatisfaction. Rather, the proportion of neutral satisfaction was found to be relatively high. This may be due to the fact that corridors are transitional spaces where occupants spend only brief periods of time. Thus, while the luminous environment in corridors may be less optimal, occupants may have a higher tolerance for such conditions. In contrast, occupants tend to spend longer periods of time in conference rooms, leading to higher expectations in terms of lighting quality and comfort. Meanwhile, occupants in office environments reported the highest level of satisfaction (with zero reports of dissatisfaction), perhaps because they spend most of their day in this environment and may have become accustomed to its lighting conditions.

The classrooms of educational buildings, particularly those in universities, exhibited a satisfaction distribution similar to that of conference rooms in office buildings. This similarity may be attributed to similarities in terms of room functions and usage patterns across these different contexts.

In contrast, hotel buildings showed a distinct pattern of satisfaction levels. While the overall satisfaction rates in guest rooms and lobbies were similar to those of offices, the level-5 satisfaction rate was much higher in these spaces, particularly in lobbies, where it reached 81%. These findings suggest that occupants had a strong appreciation for the luminous comfort of guest rooms and halls in hotels. However, occupants reported the highest dissatisfaction levels with corridors in hotel buildings, indicating that the luminous environment in these transitional spaces was relatively poor.

In both medical and commercial buildings, satisfaction levels with corridors were substantially higher than in office and educational buildings, reaching 56% and 76%, respectively. Interestingly, the satisfaction distribution in medical buildings differed from those seen in other contexts. Specifically, there was an increase in the proportion of levels 1, 2, and 5, suggesting that occupants' evaluations of the hospital's luminous environment were relatively complex, posing a challenge for improving such spaces.

In contrast, commercial buildings maintained a high level-4 satisfaction rate of around 50%. These findings highlight the importance of considering context-specific requirements when evaluating and optimizing luminous environments in public buildings.

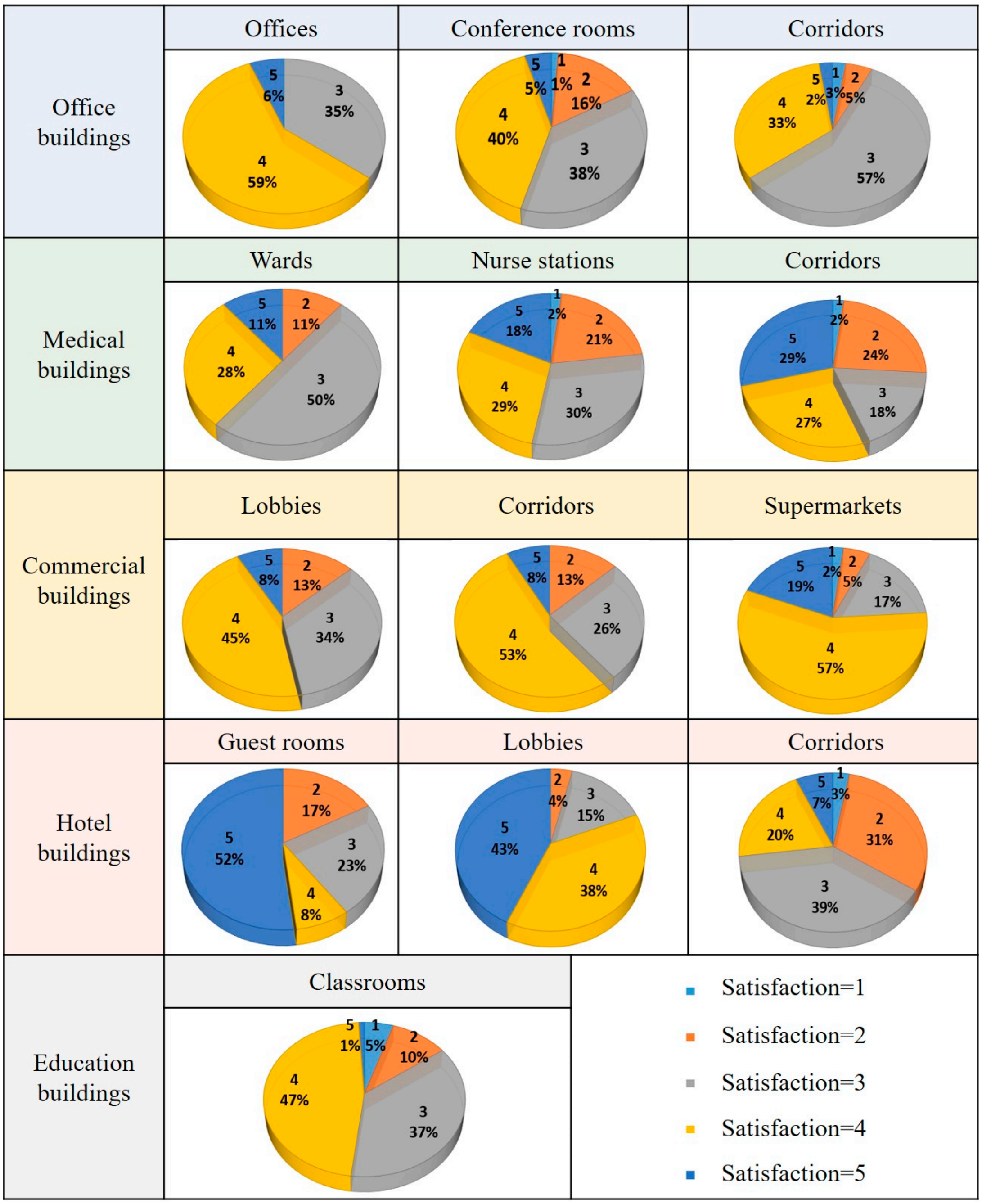

Figure 3. Overall satisfaction in public buildings.

3.2. Potential Factors for Luminous Environment Improvement

Using the five-step method described earlier, the potential factors for improving the luminous environment in different contexts of public buildings are given below.

For instance, in the case of offices within office buildings, a Spearman correlation coefficient analysis was conducted to identify subjective perceptions that had a significant impact on overall satisfaction with the luminous environment. These included spatial brightness perception, CCT perception, horizontal illuminance uniformity perception, and horizontal illuminance perception, as shown in Figure 4. The numbers represent the correlations between each subjective perception and overall satisfaction, with '*' indicating statistical significance.

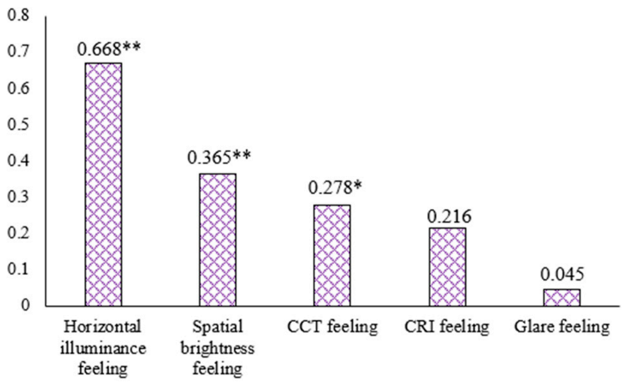

Figure 4. Subjective perceptions regarding office luminous environment. * means $p < 0.05$; ** means $p < 0.01$.

The results of the correlation analysis indicated that the perceptions related to horizontal illuminance had the strongest correlation with overall satisfaction levels among office occupants, with a correlation coefficient of 0.668 and a high significance level ($p < 0.01$ **). This suggests that horizontal illuminance plays a critical role in shaping occupants' perceptions of the luminous environment within offices. Additionally, spatial brightness was found to have a significant correlation with overall satisfaction levels in offices. Conversely, perceptions related to glare and flicker did not emerge as important factors in this context. Taken together, these findings suggest that office occupants prioritize the overall brightness and illuminance quality of their environment when evaluating the lighting conditions. As such, further research on horizontal illuminance and spatial brightness may be warranted.

However, it should be noted that a correlation coefficient with a high significance level may result in the same data distribution across different objective function groups. To more accurately determine the subjective perceptions that influence satisfaction levels in office lighting conditions, this study employed the Mann–Whitney *U* test to identify potential differences in the overall distribution of key subjective perceptions. These findings are presented graphically in Figure 5, and can help inform efforts aimed at optimizing the luminous environment within office buildings.

As shown in Figure 5, there were significant differences in the perceptions related to spatial brightness and horizontal illuminance when the overall satisfaction level with the luminous office environment was either neutral or satisfactory. These findings suggest that improving subjective perceptions of these factors may be an effective way to increase overall satisfaction levels within office environments. Interestingly, there were no significant differences observed in satisfaction levels with CCT and CRI, indicating that these factors may be less important when it comes to improving the quality of the luminous environment in offices.

Overall, the correlation and difference analyses conducted in this study highlighted the substantial impact that space luminance and horizontal illuminance can have on occupant comfort within office buildings. As such, these factors should be considered when identifying key areas for improvement. However, given that satisfaction cannot be directly improved in practice, it is essential to identify and analyze objective factors that can help guide improvements in the luminous environment. This is further illustrated in Figure 6.

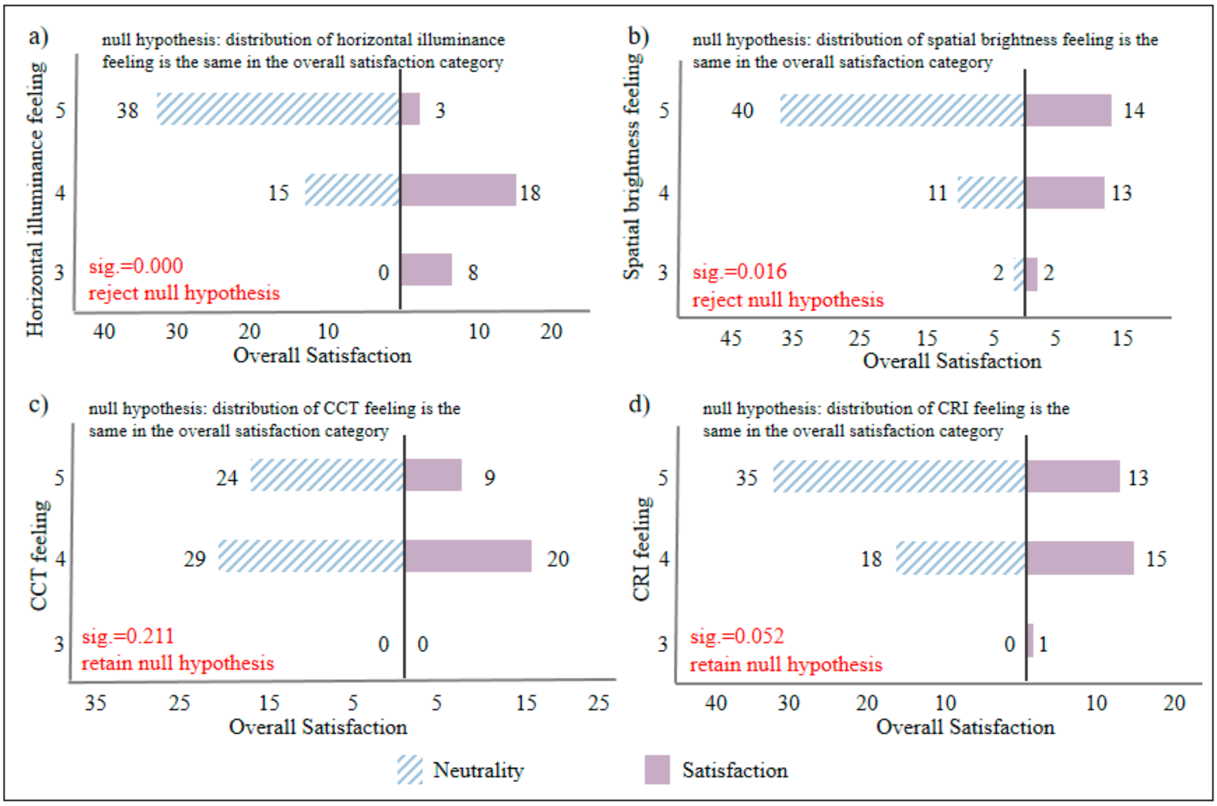

Figure 5. Analysis of the differences in office subjective satisfaction: (**a**) horizontal illuminance perception; (**b**) spatial brightness perception; (**c**) CCT perception; (**d**) CRI perception.

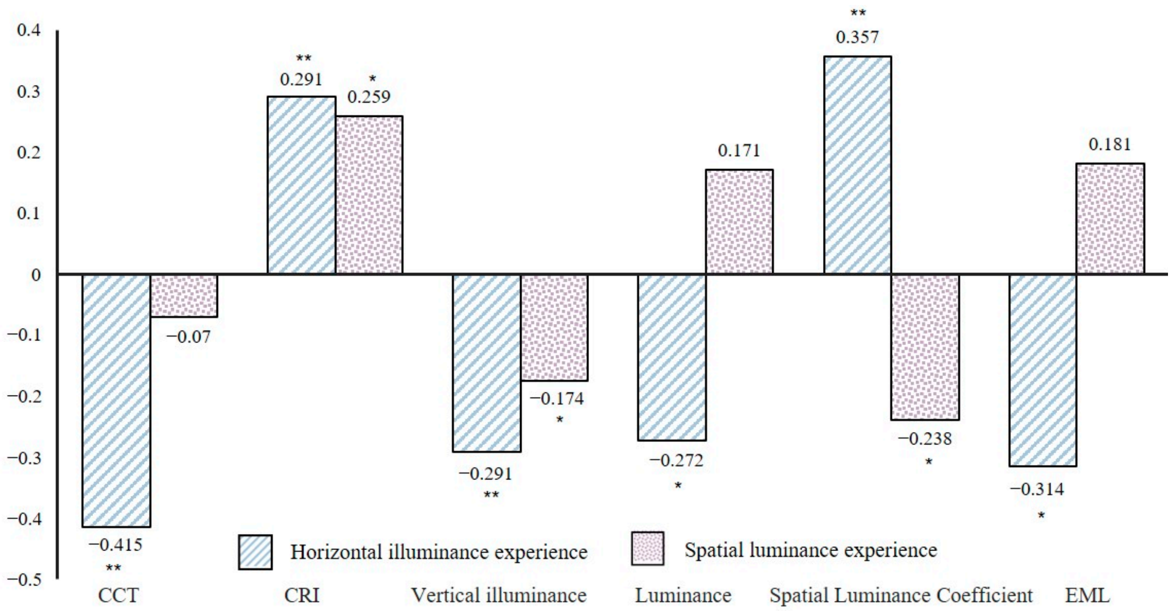

Figure 6. Objective factors that can help improve the office luminous environment. * means $p < 0.05$; ** means $p < 0.01$.

As shown in Table 4, several objective factors were found to be significantly related to the subjective perceptions described earlier, including CCT, CRI, vertical illuminance, luminance, and spatial brightness index. Of these, both CCT and the spatial brightness index were highly correlated with the subjective perception of horizontal illuminance, as well as with occupant satisfaction levels related to spatial brightness. These findings suggest that controlling CCT, CRI, and the spatial brightness coefficient may be instrumental in improving occupants' perceptions about the luminous environment in office buildings.

3.3. Thresholds of Potential Factors

In order to guide improvements to the luminous environment in a targeted manner, this study aimed to identify a reasonable threshold range for key metrics that impact occupant satisfaction levels. Using the office environment as an example, a side-by-side violin chart was created to classify satisfaction levels based on these factors, as shown in Figure 7.

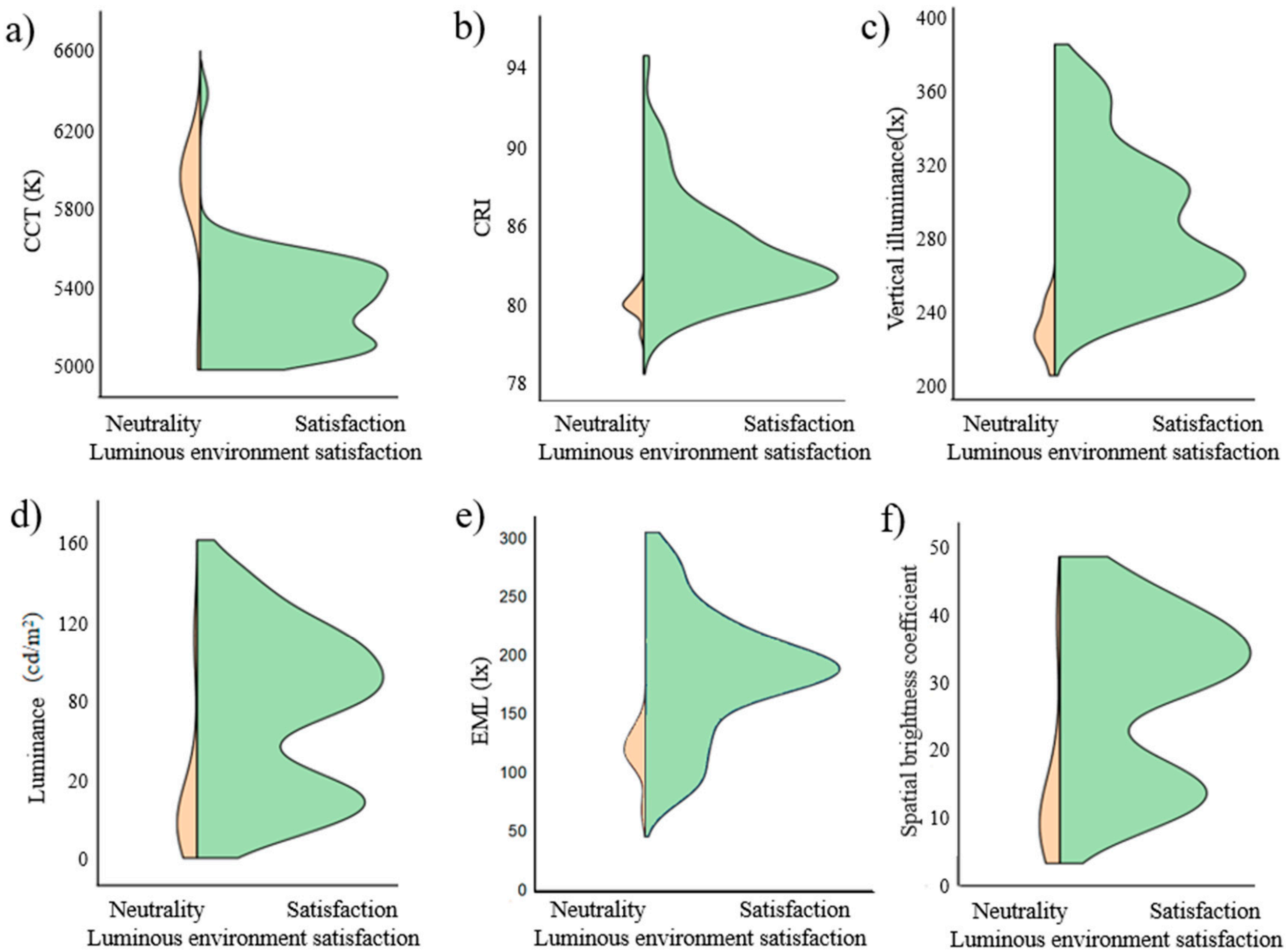

Figure 7. Relationships between the objective factors and subjective perceptions: (**a**) CCT; (**b**) CRI; (**c**) vertical illuminance; (**d**) luminance; (**e**) EML; (**f**) spatial brightness index.

To identify a reasonable threshold range for key metrics that impact occupant satisfaction levels, this study divided measured values of these factors based on occupants' perceptions in the office environment. Given the absence of a subjective perception of "dissatisfaction" in offices, the study divided satisfaction levels into categories of neutrality and satisfaction. Based on the relationship between factors and satisfaction levels, the study determined threshold values that could be used to guide improvements to the luminous environment in a targeted manner. According to thermal comfort standards, it has been observed that a certain proportion of individuals (i.e., 5%) are consistently dissatisfied with the thermal environment. Therefore, it has been proposed that the threshold for evaluating the luminous environment should be set at 95%, as a majority of individuals are expected to be satisfied under those conditions. By aiming to keep the number of people with neutral perceptions below 5%, the study found that vertical illuminance should reach 270 lx, CRI should reach 84, and CCT should be controlled below 5600 K. To optimize occupant comfort and well-being, CRI and vertical illuminance should be as high as possible. Additionally, based on Figure 7d,e, luminance should reach 40 cd/m^2, while the spatial brightness index should reach 10.

It is worth noting that the large distribution range of satisfactory values for luminance and the spatial brightness index may have been due to differences in surface reflectivity within office spaces. Moreover, the fact that occupants spend significant periods of time in these environments may mean that they have become accustomed to them, leading to a larger acceptable range of brightness levels for human eyes. Overall, this study established that while the luminance and spatial brightness index are highly correlated with occupant perceptions about the luminous environment, they should be used more as basic factors to set limits rather than as indicators of comfort.

3.4. Luminous Environment Improvement System for Office Buildings

The parameters and corresponding thresholds for improving the luminous environment in office buildings are summarized in Table 5. The first column of the table presents the details of the Chinese Standard for Lighting Design of Buildings [45], with the aim of presenting the levels of output derived from this research that should be increased for future standard recommendations.

Table 5. Parameters and thresholds for improving the luminous environment in office buildings.

Parameter	Chinese <50034> Current Standard	Satisfaction Increased	
		Increased to Neutrality	**Increased to Satisfaction**
Horizontal illuminance	Office/Meeting room ≥ 300 lx; Corridor ≥ 50 lx	Meeting room ≥ 400 lx; Corridor ≥ 65 lx	Meeting room ≥ 500 lx; Corridor ≥ 100 lx
Uniformity of illuminance	Office/Meeting room/ Corridor ≥ 0.6	Meeting room ≥ 0.75	Meeting room ≥ 0.85; Corridor ≥ 0.75
Vertical illuminance	Not defined		Office ≥ 270 lx;
Luminance	Not defined	Meeting room ≥ 15 cd/m^2	Office/Meeting room ≥ 40 cd/m^2
CRI	Office/Meeting room ≥ 80; Corridor ≥ 60	Meeting room ≥ 83	Office ≥ 84; Meeting room ≥ 85; Corridor ≥ 80
CCT	Office/Meeting room ≥ 3300 K	Corridor ≥ 4000 K	Office ≤ 5600 K
Spatial brightness index	Not defined	Corridor ≥ 3	Office ≥ 10
Luminance contrast	Not defined		Meeting room ≥ 0.3

The findings presented in Table 5 do not provide a clear threshold value for parameters that can enhance the satisfaction level of the office luminous environment from dissatisfaction to neutrality. This is primarily due to the exclusion of data that fail to meet current standards, thereby eliminating instances of dissatisfaction in the analyzed samples. Moreover, the comparable brightness requirements and visual factors between office and meeting rooms suggest minimal differences between these two contexts.

4. Discussion

4.1. Comparative Analysis of Different Public Buildings

Building on the analytical process employed for office buildings, the research investigation was extended to encompass all five categories of public buildings. The outcomes of this extension are reported in Tables 6–9, with Table 6 specifically detailing the parameters and threshold values that can augment the luminous environment within educational buildings.

Occupants of office and educational buildings spend substantial amounts of time working or studying within these environments. The established standards for these building types currently share similar criteria and threshold values within typical settings. Through this study, it was discovered that illuminance and uniformity were nearly identical across both contexts, while brightness exhibited a notable gap between them. Specifically, the highly reflective desktops in educational buildings contributed to the measured brightness values, which, however, did not negatively impact occupant satisfaction. Furthermore, high wall reflectivity allows for proportional reductions in illumination requirements, corroborating prior research findings [55]. Overall, this study suggests that task illuminance satisfaction can be effectively achieved through reasonably high room surface reflectance.

Table 6. Parameters and thresholds for improving luminous environment in educational buildings.

Parameter	**Chinese <50034> Current Standard**	**Satisfaction Increased**	
		Increased to Neutrality	**Increased to Satisfaction**
Horizontal illuminance	$\geq$300 lx	$\geq$350 lx	$\geq$450 lx
Uniformity of illuminance	Desk horizontal $\geq$ 0.6; Blackboard $\geq$ 0.8	Desk horizontal $\geq$ 0.8; Blackboard $\geq$ 0.85	Desk horizontal $\geq$ 0.9; Blackboard $\geq$ 0.9
Vertical illuminance	Not defined	$\geq$300 lx	$\geq$300 lx
Luminance	Not defined	Desk $\geq$ 30 cd/m^2; Blackboard $\geq$ 10 cd/m^2	Desk $\geq$ 45 cd/m^2; Blackboard $\geq$ 15 cd/m^2
CRI	$\geq$80	$\geq$83	$\geq$85
CCT	$\geq$3300 K	$\geq$5000 K	5000–5600 K
Spatial brightness index	Not defined	$\geq$10	$\geq$15
Luminance contrast	Not defined	Desk horizontal $\leq$ 0.8; Blackboard $\leq$ 0.9	Desk horizontal $\leq$ 0.5; Blackboard $\leq$ 0.7

Table 7. Parameters and thresholds for improving luminous environment in medical buildings.

Parameter	**Chinese <50034> Current Standard**	**Satisfaction Increased**	
		Increased to Neutrality	**Increased to Satisfaction**
Ground illuminance	Ward $\geq$ 100 lx; Corridor $\geq$ 100 lx	Nurse station $\geq$ 150 lx	Ward $\geq$ 200 lx; Nurse station $\geq$ 250 lx; Corridor $\geq$ 150 lx
Uniformity of illuminance	Ward $\geq$ 0.6; Corridor $\geq$ 0.6	Nurse station $\geq$ 0.7; Corridor $\geq$ 0.65	Nurse station $\geq$ 0.8; Corridor$\geq$ 0.7
Vertical illuminance	Not defined	Nurse station $\geq$ 40 lx	Ward $\geq$ 50 lx Nurse station $\geq$ 75 lx
Luminance	Not defined	Ward $\geq$ 20 cd/m^2; Corridor $\geq$ 20 cd/m^2	Corridor $\geq$ 25 cd/m^2
CRI	Ward/Nurse station $\geq$ 80; Corridor $\geq$ 60	Corridor $\geq$ 80	Ward/Nurse station/ Corridor $\geq$ 85
CCT	Not defined	Ward $\geq$ 4200 K; Nurse station $\geq$ 4200 K; Corridor $\leq$ 5500 K	Ward: 4200–4500 K Nurse station: 4200–5400 K; Corridor: 4000–5500 K
PF	Ward $\leq$ 0.03	Nurse station $\leq$ 0.25	Ward $\leq$ 0.2
Flicker index	Not defined	Nurse station $\leq$ 0.15	Ward $\leq$ 0.1

Table 8. Parameters and thresholds for improving luminous environment in business buildings.

Parameter	Chinese <50034> Current Standard	Satisfaction Increased: Increased to Neutrality	Satisfaction Increased: Increased to Satisfaction
Groundilluminance	Hall $\geq$ 200 lx; Market $\geq$ 100 lx; Corridor $\geq$ 100 lx		Corridor $\geq$ 150 lx; Market $\geq$ 300 lx;
Uniformity of ground illuminance	Hall $\geq$ 0.6; Market $\geq$ 0.6; Corridor $\geq$ 0.4	Corridor $\geq$ 0.6	Corridor $\geq$ 0.85; Market (commodity area) $\geq$ 0.8; Market (meat area) $\geq$ 0.85
Vertical illuminance	Not defined	Corridor $\geq$ 50 lx	
Luminance	Not defined	Commodity shelves $\geq$ 50 cd/m^2; Fruit and vegetable area $\geq$ 50 cd/m^2	Hall $\geq$ 75 cd/m^2; Commodity shelves $\geq$ 75 cd/m^2; Meat area/Fruit and vegetable area $\geq$ 100 cd/m^2
CRI	Hall $\geq$ 80; Market $\geq$ 80; Corridor $\geq$ 60	Market (fruit and vegetable area) $\geq$ 83	Hall $\geq$ 85; Market (meat area) $\geq$ 83; Corridor $\geq$ 85
CCT	Not defined	Market (meat area) $\geq$ 2600 K	Corridor $\geq$ 3300 K; Market (meat area) $\geq$ 3200 K
PF	Not defined	Market (fruit and vegetable area) $\leq$ 0.4	Hall $\leq$ 0.1; Market (fruit and vegetable area) $\leq$ 0.25
Flicker index	Not defined	Market (commodity area) $\leq$ 0.15; Market (meat area) $\leq$ 0.25	Market (commodity area) $\leq$ 0.1; Market (meat area) $\leq$ 0.1

Table 9. Parameters and thresholds for improving luminous environment in hotel buildings.

Parameter	Chinese <50034> Current Standard	Satisfaction Increased: Increased to Neutrality	Satisfaction Increased: Increased to Satisfaction
Horizontal illuminance	Guest room(bed) $\geq$ 150 lx; Guest room(desk) $\geq$ 300 lx; Hall $\geq$ 200 lx; Corridor $\geq$ 50 lx	Hall $\geq$ 240 lx; Corridor $\geq$ 70 lx	Hall $\geq$ 280 lx; Corridor $\geq$ 100 lx
Uniformity of illuminance	Hall/Corridor $\geq$ 0.4; Corridor $\geq$ 0.4	Guest room (bed/desk/ground) $\geq$ 0.7; Corridor $\geq$ 0.55	Guest room(bed/desk) $\geq$ 0.75; Corridor $\geq$ 0.65
Vertical illuminance	Not defined	Hall $\geq$ 50 lx;	Hall $\geq$ 100 lx;
Luminance	Not defined	Guest room $\geq$ 30 cd/m^2; Hall $\geq$ 75 cd/m^2; Corridor $\geq$ 20 cd/m^2	Guest room $\geq$ 50 cd/m^2; Hall $\geq$ 100 cd/m^2; Corridor $\geq$ 75 cd/m^2
CRI	Guest room/Hall/Corridor $\geq$ 80		Guest/Hall) $\geq$ 85; Corridor $\geq$ 84
PF	Not defined	Guest room $\leq$ 0.3	Guest room $\leq$ 0.1
Flicker index	Not defined	Guest room $\leq$ 0.1	
Spatial brightness index	Not defined		Corridor $\geq$ 10

Medical buildings place a special emphasis on CCT thresholds, with a prevailing orientation of "the higher the CCT, the better the luminous environment". However, in settings involving nocturnal activities such as wards (Table 6), controlling the shortwave component becomes crucial in reducing patient alertness and promoting recovery. Research has established the upper limit of CCT in wards at 4500 K, given that public buildings, notably medical facilities, demonstrate lower levels of satisfaction under high CCT. Consequently, it is necessary to restrict the upper limit of CCT. This need is further accentuated by patient preferences for a comfortable and warm lighting environment, as patient room lighting requirements prioritize object recognition over reading. While medical buildings generally exhibit lower luminous intensity demands compared to other building types, their requirements for CCT and CRI remain consistent. This highlights the critical nature of color representation in the luminous environment, with a recommended CRI threshold of 85 in wards that prioritize enhancing patient comfort and warmth.

The parameters and thresholds required to improve the luminous environment quality in business and hotel buildings are shown in Tables 8 and 9.

The surveyed commercial buildings exhibited a relatively high level of brightness within their luminous environments. Given that the upper limit of illuminance was set, commodity booths were also outfitted with local lighting. Commercial and hotel buildings share comparable key metrics and threshold values for their respective luminous environments; however, the former displays higher environmental demands. Notably, the recommended thresholds for existing parameters in public building luminous environment evaluations have been enhanced compared to the established standards for lighting design [42]. Moreover, newly identified parameters such as the spatial brightness coefficient, vertical illuminance, EML, luminance, and luminance contrast have been incorporated into these evaluations.

4.2. Negative Correlations between Subjective Feelings and Objective Factors

The negative relationship between CCT and horizontal illuminance satisfaction, as reflected in Figure 6, is a noteworthy finding from this study. The correlation coefficient was −0.415, which is statistically significant at a high level ($p < 0.01$). This phenomenon is explained and discussed below as illustrated in Figure 8.

The relationship between office luminous environment satisfaction and horizontal illuminance satisfaction is positively correlated, as demonstrated in Figure 4 (0.668 **). However, the CCT range that satisfies occupants is concentrated within the middle range, indicating a negative correlation. This is especially true for artificial lighting environments during nighttime hours, where it proves challenging to satisfy occupants with a cool CCT of 6000 K. No significant improvements in subjective perception were observed under other conditions. Consequently, determining an optimal CCT control is crucial, with an ideal value of around 5400 K.

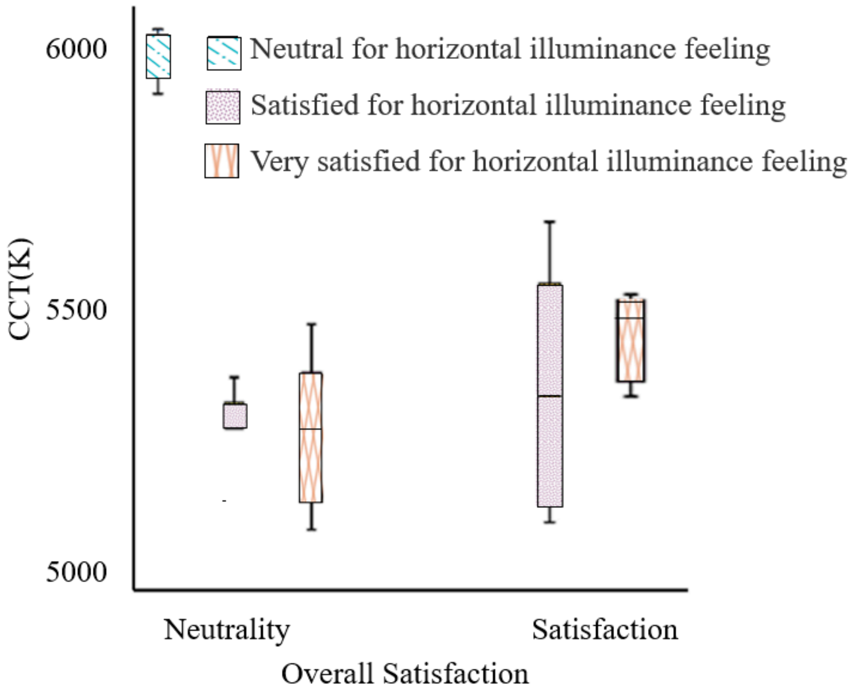

Figure 8. CCT distribution in office setting.

4.3. Thresholds of Illuminance, CCT

Illuminance and CCT are widely recognized as critical factors that influence perceptual comfort and preference [17,56]. Consequently, determining optimal thresholds and preferences has remained a central focus of lighting research, as demonstrated in Table 10.

Table 10. Related studies on the luminous factors.

Researcher	Experimental Methods	Subjects	Experimental Space	Factor Conditions	Conclusions
Rui Dang et al. 2018 [57]	Questionnaire (satisfaction). 20 min	27 students	Clothing store simulated in a laboratory	200, 500, 1000, 1500 lx; 3000, 4500, 6000 K	Highest evaluation: 1000 lx and 4500 K
Naoyuki Oi et al. 2017 [58]	Questionnaire (preference, brightness, naturalness)	8 students	Settings for "relaxing" and "studying"	50, 100, 200, 400, 800 lx; 3000, 4200, 5000, 6500 K	Preference depends on the activities. Studying: high illuminance. Relaxing: low CCT
Stéphanie van der Lely et al. 2014 [59]	Cognitive tests, scales, saliva samples	13 male students	Laboratory with blue light-enriched LED screen	400–480 nm of screen was 0.32 W/(sr*×m^2)	Blue light reduction decreased vigilant attention and alertness at night
Jae Hoon Ma et al. 2022 [60]	cognitive tasks, visual perception questionnaire	13 male students	Immersive virtual environments	200, 500, 750 lx; 2000, 4000, 6500 K	4000 K was the most naturally perceived CCT and obtained highest score task at all illuminance levels
Jiayi Bao et al. 2021 [61]	Questionnaire (Task Load Index), EEG	12 students	Laboratory simulated in an office	300–1000 lx; 3000–6500 K	Lowest mental workload: 3000 K and 750 lx
Yan Yonghong et al. 2015 [62]	The change rate of students' α and β brain waves	2 students	Classroom simulated in a laboratory	300, 750, 1000 lx; 2700, 4000, 6500 K	Brain fatigue comes earlier at high illuminance and high CCT illumination
This study	Questionnaire (satisfaction) and field study	1423 volunteers	Actual context in public buildings	300–1000 lx; 2500–6500 K	CCT: >3300 K in business buildings, ≤5600 K in office buildings

Fotios S have asserted that CCT variation has a negligible effect on brightness and pleasantness ratings [30]. However, other scholars have discovered that a luminous environment with a medium CCT and high illuminance (1000 lx, 3500 K) is satisfactory for commercial buildings or relaxing settings [57]. Similarly, Oi et al. found that a low CCT and high illuminance environment was preferable for relaxation, while a high CCT and high illuminance environment was suitable for work [58]. These findings align with the conclusions drawn from our study, as reflected in Tables 5–9. While there are two possible reasons for the CCT conclusion drawn in this study, namely the influence of uncontrollable variables under field conditions and the restrictions on lighting settings under fixed environment satisfaction surveys, it is worth noting that our investigation allowed for CCT and illuminance adjustments during testing. Volunteers did not prefer environments with extremely low or high CCT values, indicating that their preferences and comfort levels were effectively reflected. Jae Hoon MA compared task scores and perception scores between 4000 K and 6500 K light environments, revealing that the former surpassed the latter, implying that a high CCT is insufficient in meeting personnel office needs [60]. Additionally, blue-rich lighting has been shown to improve performance, reduce subjective sleepiness, affect the circadian system, lengthen sleep latency, and prevent cognitive fatigue [59–62].

4.4. Limitations

While the investigation results provided an accurate reflection of on-site requirements, it should be noted that investigations conducted in medical buildings revealed that most wards turned off their lights by 19:30. Additionally, when lights were turned on at night, a lower luminance mode was often selected, thus potentially limiting the analysis results.

Another limitation of this study was the use of a five-point scale for evaluation. While such scales are widely used and can provide reliable results, some psychometricians recommend using seven or even nine levels to obtain more accurate and precise data.

5. Conclusions

Based on the investigation and objective measurements for public buildings among four cities in China, a set of analysis methods was developed and employed to identify objective factors and thresholds required to improve luminous environment satisfaction under different contexts. These findings provide a theoretical basis that could assist government officials and researchers in updating existing standards, enhancing their understanding of such standards, and facilitating further research aimed at creating better luminous environments in the future. The specific conclusions are as follows:

(1) Current lighting standards were met in over 60% of public building contexts.

Based on the results, once all indicators comply with the standards, the personnel satisfaction rate can exceed 30%. To establish a comfortable and effective light environment, the building should aim to maximize color rendering while still meeting the illuminance standard. To enhance user productivity and attention, incorporating lighting control strategies like intelligent color temperature adjustment in buildings is recommended.

(2) Different environments have distinct demands for optimizing the lighting conditions.

Through a descriptive analysis of both subjective and objective results, it was found that distinct contexts have specific requirements for enhancing the luminous environment. For example, office buildings and educational buildings are places where occupants typically work or study for extended periods. In these contexts, occupants place emphasis on the perception of horizontal illuminance, with those working in office buildings also paying attention to the perception of space brightness and those in educational buildings additionally considering the perception of CCT. The differing scene requirements necessitate the adoption of various classic, new, and updated factors for evaluating comfort levels. These factors include CRI, CCT, vertical illuminance, luminance contrast, and spatial brightness index.

(3) By utilizing a specific set of metrics and thresholds, the required level of improvement in each scenario was quantified.

This study identified key metrics and their corresponding thresholds to enhance the light environment in office buildings (Table 5), educational buildings (Table 6), medical buildings (Table 7), commercial buildings (Table 8), and hotel buildings (Table 9) across three levels: unsatisfactory, neutral, and satisfactory. Taking an office as an example, to increase satisfaction with the luminous environment from neutral to satisfactory, the CCT should be controlled below 5600 K. Additionally, the vertical illuminance, luminance, and spatial brightness coefficients should reach 270 lx, 40 cd/m^2, and 10, respectively.

The research findings have identified key metrics and thresholds necessary for improving luminous comfort in public buildings and could guide future lighting design, LED technology, and daylighting integration technology.

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Appendix A

The specific content of the questionnaire is as follows:

Office building luminous environment questionnaire

1. Gender □male □female
2. Age □20-30 □30-40 □40-50 □more than 50
3. Wear glasses □often □sometimes □never
4. Work hour □3-5h □5-7h □7-9h □more than 9h
5. Office tool □Computer office □Desktop office □There is not much time difference between the two
6. Relative position to the window □facing it □back to it □side to it □others
7. When you work in the luminous environment, do you feel serious distortion (color rendering) when you observe the color of the object? □very serious □serious □a little □slight □never
8. Is the light source flickering serious? □very serious □serious □moderate □not serious never

9a. How would you describe the uniformity of illuminance on a horizontal work surface in the office? □very uneven □uneven □acceptable □even □very even

9b. Are there dark or bright areas in the office (where you are) that interfere with your normal work or make you uncomfortable? □usually □often □sometimes □hardly □never

10a. How would you describe the lighting levels at your location in the office while working in? □very weak □weak □moderate □strong □very strong

10b. Based on the existing light environment, the lighting level you would expect (in your location) is? □very weak □weak □moderate □strong □very strong

11a. How would you describe the lightness and darkness of your workspace in? □very dark □dark □moderate □bright □very bright

11b. Based on your existing light environment, you would expect the following environment (your workspace) to be as bright and dark as? □very dark □dark □moderate □bright □very bright

12a. The perception of warmth and coldness (CCT) brought by the light source when you work/active in the office □very cold □cold □moderate □warm □very warm

12b. Based on the existing light environment, the perception of cool and warm (CCT) you expect from the light source in the office is: □very cold □cold □moderate □warm □very warm

13a. Do you often experience discomfort from dazzling your eyes (glare) while working in office? □usually □often □sometimes □hardly □never

13b. Please select which type of glare you feel most uncomfortable. □sunlight □artificial light □reflected light □sky too bright □direct light to computer

14. When working, how would you rate the overall satisfaction with the light environment of office? □very dissatisfied □dissatisfied □moderate □satisfied □very satisfied

15a. Do you become distracted by working in this environment for a long time? □usually □often □sometimes □hardly □never

15b. Does being in this work environment for a long time affect your nighttime rest (poor sleep quality/your time to fall asleep)? □very serious □serious □slight □hardly □never

15c. Does the lighting environment in office make you happy when working/activity? □very unpleasant □unpleasant □fair □pleasant □very pleasant

15d. Which of the following situations are you more concerned about? □distraction □rest at night □feeling pleasant

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