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Study of Human Visual Comfort Based on Sudden Vertical Illuminance Changes

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Abstract: Rapid changes in vertical illuminance trigger visual fatigue. Therefore, controlling the illuminance ratio of adjacent spaces can ensure the satisfaction and comfort of users. This study takes reaction time as the measure of adaptation and explores the correlation between visual adaptation and comfort in different light environments. The Landolt C ring was selected as the visual standard for the experimental test, the degree of visual comfort was assessed using a Likert scale, and experimental parameters were formulated according to relevant criteria. By analyzing the subjective visual comfort, visual task performance and physiological evaluations of the participants under different changing illuminance levels, we have concluded that there is a significant correlation between reaction time and visual comfort, and no significant effect of gender on visual comfort. Therefore, under the condition of meeting the required value of illumination standard, the smaller the illuminance ratio of adjacent rooms, the more the comfort and visual acuity of users can be guaranteed, and visual fatigue can also be avoided. The study is a useful resource for improving comfort and pleasure in a light environment as well as for lighting design.

Keywords: vertical illuminance; visual comfort; building light environment; correlation analysis; experimental research

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1. Introduction

As people's living standards rise, they have more and more demands for buildings with light environments, and there is increased attention on energy-saving technology and the requirements for visual comfort. As stated by Linhart and Scartezzini [1], "Electricity consumption and energy-efficiency are not the only topics to consider when it comes to designing appropriate lighting scenarios for buildings: good visual comfort is of course equally important". There are more factors influencing the comfort of the light environment, including discomfort caused by physical factors such as uncomfortable lighting or glare that irritate the human eye, but also the subjective psychological feelings of people [2,3]. Slater [4] proposed that comfort consists of the physiological feelings and psychological feelings of people in an environment in which they are in a pleasant state; Hertzberg [5], IACOMUSSI P, et al. [6] believed that comfort is the absence of uncomfortable feelings. Visual comfort is defined in the European standard EN 12665 as "a subjective condition of visual well-being induced by the visual environment" [7]. The current methods for determining visual comfort include the "no annoyance method" [8,9]. Another approach is based on subjective evaluation [10]. Several studies have shown that people prefer the comfort of natural light [11,12], which, in terms of physiological factors, provides great advantages for the health and wellbeing of the residents, psychological aspects, etc. [13,14]. In 1947, Moon and Spencer in the United States were the first to study the effect on human visual physiology from the perspective of illuminance, and the study concluded that higher illuminance is better, but did not propose an upper limit of illuminance because of the conditions [15]. However, individuals differed significantly in their perceptions of visual comfort [16,17].

Low-illumination environments and illumination adaptation states may lead to eye strain [18]. When people walk from a darker space to a brighter space, their eyes experience a series of discomforts such as photophobia. Therefore, controlling the illuminance ratio of adjacent spaces can ensure the health and comfort of users.

2. Literature Review

The human brain responds differently to light information under different light conditions. Moreover, a suitable light environment can reduce stress, improve anxiety, and avoid negative emotions [19]; bright light treatment has been proven to be very effective for treating seasonal mood disorders in numerous clinical investigations [20]. Carlucci et al. [21] studied the review of comfort [21]. Loe et al. [22] analyzed the visual effects of 18 lighting conditions based on human subjective perception and obtained 2 important variable factors: visual interest and visual luminosity.

Liu Gang and Dang Rui et al. [23] investigated the effects of illuminance, illuminance uniformity, and relevant color temperature on visual comfort through evaluation experiments. The subjective evaluation questionnaire set up a 7-level scale of subjective evaluation according to the comfort level, where 1 represents extremely uncomfortable and 7 represents very comfortable. Thirty participants conducted subjective evaluation experiments under different lighting conditions in the dimming control system and concluded that the office lighting design should control the illuminance between 200–300 lx and control the color temperature in the middle color temperature, which can satisfy the comfort level and maximize the energy saving of lighting. Mingli Lu et al. [24] analyzed the subjective evaluation, task performance, and physiological data of staff under different combinations of three color temperatures and five illumination levels. Mingli Lu et al. [24] analyzed the results of subjective, task, and physiological evaluations of staff under different combinations of five illuminance levels and three color temperatures. The subjective evaluation was performed on a 5-point scale, with -4 representing extreme discomfort and 0 representing comfort, and the subjective evaluation showed that illuminance had a highly significant effect on the perception of color fidelity, spaciousness, fatigue, and relaxation, while color temperature affected only the perception of spaciousness. Within the scope of the study, improved illumination of the working environment contributed to improved light comfort, but with a decreasing trend. Kompier Maaike E et al. [25] studied the temporal dynamics and inter-individual variability of subjective perception, comfort, and mood evaluation, following abrupt changes in illuminance and color temperature, and showed that this effect could be due to the change of illumination or CCT and that responses to sudden changes in both always occurred immediately.

3. Methods

3.1. Study Overview

To study the change law of visual adaptation in the process of illuminance changes in different building spaces, it is necessary to simulate different combinations of illuminance changes in the laboratory environment, and to investigate the effects of these different illuminance changes on adaptation time and comfort, including the correlation between reaction time and subjective comfort evaluation, and to infer whether objective data such as reaction time can be used to determine visual comfort.

3.2. Experimental Methods

The methods of evaluating the comfort of the light environment include subjective and objective evaluation methods [26]. The subjective evaluation method is used by people to perceive the environment, using their eyes and ears, and other sensory organs, to obtain effective information, which is processed by the brain to evaluate the environment [27].

Subjective evaluation is simple to operate and easy to analyze. The objective evaluation method is to measure the physical parameters of the environment and the physiological responses of the user sample through professional instruments, establish a mathematical model between them, and thus derive the results through data analysis [28]. In this experiment, a combination of subjective and objective evaluation was used to evaluate the visual comfort experiment.

3.2.1. Subjective Evaluation

The questionnaire is based on the Likert scale, with a five-point scale [29], based on the "positive-negative" rule proposed by Laporte. It can be ranked in order as extremely uncomfortable, less comfortable, moderate, more comfortable, and extremely comfortable, expressed by the numbers -2 to 2.

3.2.2. Subjective Evaluation

The experimental method for studying visual adaptation uses the visual efficacy method, and the reaction time is chosen to characterize the visual efficacy of the human eye under illuminance changes. The reaction time is defined as the time from stimulus onset to the observer's response [30], i.e., how quickly the participant can accurately detect and respond to the next target, i.e., including both the human eye's observation time and the body's reaction time. We experimentally tested subjective visual comfort and visual task performance under changing illuminance levels. Before using the experimental method of visual efficacy to build a reaction time testing system, it is necessary to design a reasonable experimental setup, experimental parameters, and experimental procedure.

Figure 1 shows the Landolt c-ring as the visual target used in the experiment. The Landolt ring has a diameter of 75 mm, a width of 15 mm, and an opening of 15 mm. The size of the test board was 300 mm × 300 mm. The Landolt ring is sometimes used to test visual acuity, so the participant's visual or corrected visual needs to be good to avoid experimental errors. The Landolt ring was printed by the photographic method on an unlit white paper with a reflectance ratio ρ = 0.82, and the opening orientation of the Landolt ring appeared randomly [31]. There are 8 directions of Landolt ring openings. Ikeda, K et al. used Landolt rings to study visual acuity as a function of adaptive luminance [32].

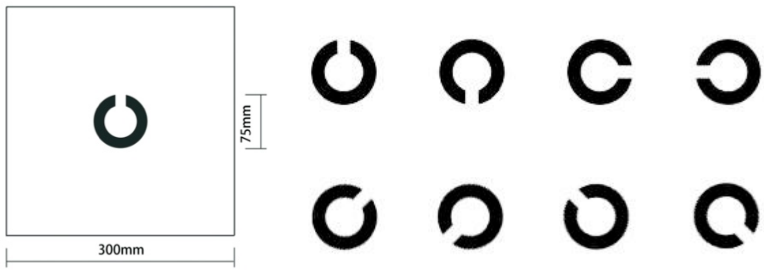


Figure 1. Visual target—landolt c.

3.3. Experimental Design

3.3.1. Experimental Setup

Using the experimental method of visual efficacy to establish the visual adaptation time test system, the experimental setup is mainly divided into two parts: one part is the test box part and the other part is the control part. Figure 2 shows the design of the experimental setup: 1-test box; 2-gloss-free white paper board; 3-turn shaft; 4-coupling; 5-step motor; 6-converter; 7-wire; 8-test button; 9-DC power supply; 10-TSC89752 type microcontroller; 11-control button.

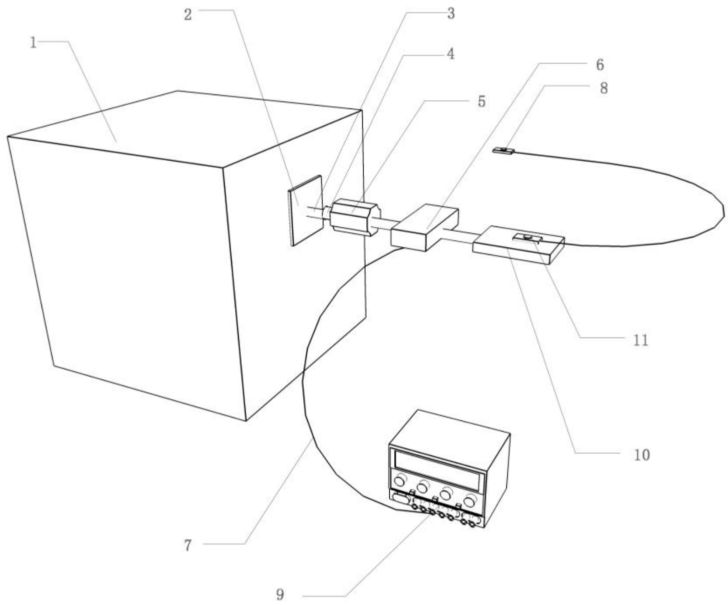


Figure 2. Design drawing of the experimental device.

1. Test box part

The test section of the experimental setup consists of an empty rectangular box, an adjustable LED strip, and a light-free white test board printed with Landolt C-rings, as shown in Figure 3.

Figure 3. The test box part of the experimental device.

The main part of the test chamber is an opaque, uncovered rectangular box consisting of five white chevron panels with a uniform reflection ratio inside the box. The uncovered side of the rectangular box was facing the subject, and a square hole was made at the eye level of the participant, the size of which was smaller than the unlit white paper test board, where the Landolt C-ring was located. During the experiment, the white paper board is pressed against the box without leaving a gap. Inside the box is installed an LED induction dimming light—an LED induction remote control dimming light with regulation remote control—which can realize from the remote end of the precise control. The position of the induction lamp will not have a glare effect on the human eye and make the brightness distribution in the space even. The LED lamp is tested in the experimental environment and the maximum illuminance of the test point can be adjusted to 10–12,000 lx. The angle of the lamp is oriented towards the light-free white paper board, where the Landolt C ring is located, forming a diffuse light environment that prohibits direct light into the subject's eyes to avoid glare. The test box does not affect the participant's visual field, and the visual target is also in the central visual field, as shown in Figure 4.

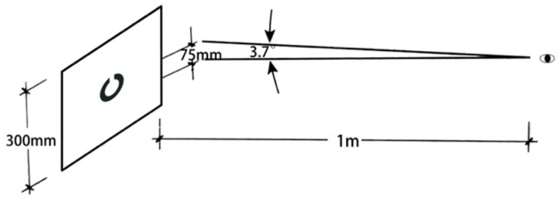
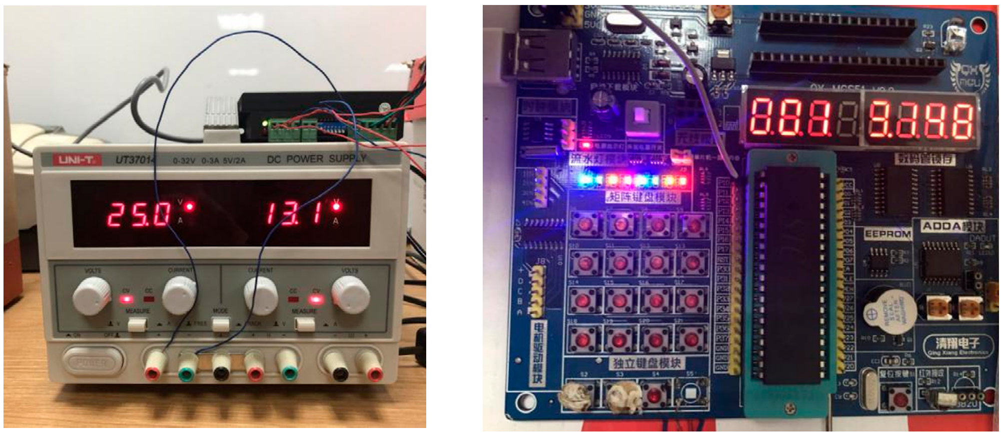


Figure 4. Visual angle.

2. Control section

The control part of the experimental device consists of a TSC89752 microcontroller, stepper motor, DC power supply, control buttons, and remote control, as shown in Figure 5. The LED induction lamp has a tester using a remote control at the rear. The whiteboard where the Landolt ring is located is taped to the motor, and a stable voltage is output through a regulated DC power supply, which is connected to the microcontroller and motor with a set program. The microcontroller is connected to a control button for the subject to press after identifying the direction of the opening. The microcontroller has a time display board to record the time from when the motor stops rotating to when the subject presses the button.



(**a**) (**b**)

Figure 5. Photos of the control part of the experimental device. (**a**) DC power supply. (**b**) Single chip microcomputer.

In the experiment, a TSC89752 microcontroller was used as the processing front-end. As the subject makes a judgment on the direction of the opening in the "C" test board at the box window in different environments, the microcontroller will upload the subject's reaction time data to the PC, and after pressing the control button, the information will be fed back to the stepper motor to complete the rotation of the test board. At the end of the single-person, single-group experiment, the program will generate a data set that contains only the human adaptation speed corresponding to each test board under the corresponding environmental conditions. Figure 4 shows the control part of the experimental setup.

3.3.2. Experimental Instrument

1. Full digital colorimeter and illuminance meter

An XYC-I full digital colorimeter and TES 1332A illuminance meter were selected for the experiment, as shown in Table 1. XYC-I colorimeter can achieve full range measurement, high accuracy, handheld and portable, and can be used for rapid measurement of illuminance, color temperature, and other related parameters. Two measuring instruments can be used simultaneously, thus improving the accuracy and avoiding experimental errors.

Table 1. Experimental instrument table.

Instrument Name	**Colorimeter**	**Illuminometer**	**LED Step-Less Control Lamp**	**Blood Pressure Monitor**
Pictures				
Measurement range	0.1–50,000 lx	0.1–99,990 lx	10–12,000 lx	Nominal pressure range is 0 to 299 mmHg (±3 mmHg), pulse rate 40 to 180 bpm (±5%)

2. Induction lamp

LED induction dimming lamp is a key part of the experimental device; it can provide different levels of brightness to the light environment. LED induction remote control dimming lamp is equipped with a control remote control; multi-position can achieve precise control from the remote end. The position of the induction lamp does not affect the glare of the human eye, and the illuminance is evenly distributed in the space. The LED induction lamp in the experimental environment measured the illuminance range can be adjusted in the middle of 10–12,000 lx. The spectral power distribution of the light source is shown in Figure 6.

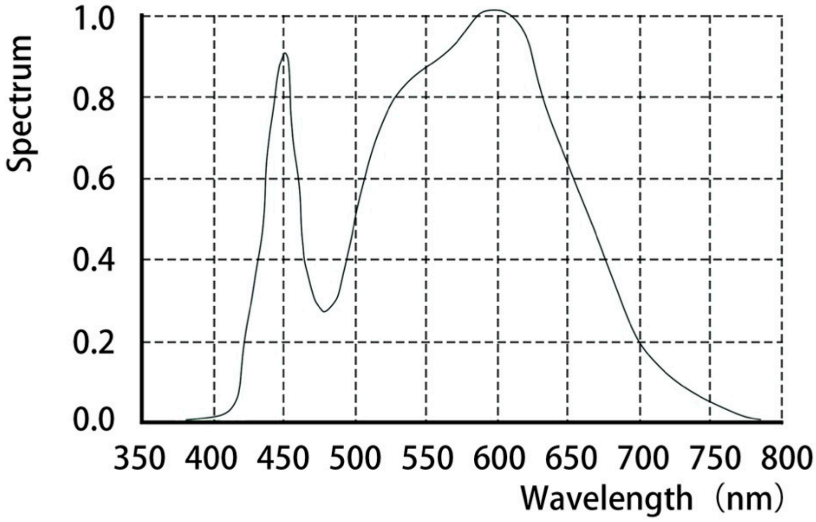


Figure 6. The spectral power distribution of the light source.

3. Physiological parameter meter

The wrist sphygmomanometer was selected as the human physiological parameter meter in the experiment for measuring the heart rate changes of the participants before and after the experiment, and the heart rate increased with the increase of viewing visual fatigue, and visual fatigue has a good consistency, and the measurement is simple and can be used as an index of visual fatigue assessment [33]. For quick and accurate measuring of the blood pressure and heart rate data of the participants in the experiment, an OMRON-HEM-8612 type home type wrist blood pressure monitor was used.

3.3.3. Experimental Parameter Setting

Correlated color temperature in 3300 K to 5300 K is intermediate color appearance. The choice of color temperature depends on the illuminance and the color of the room [34]. The color temperature is set to 4000 K in the experiment.

When the illuminance changes by 1.5 times, it is the smallest difference that people can feel subjectively. The minimum illuminance at which people can identify information is 20 lx. According to the recommended illuminance value in the CIE standard, we set the experimental parameters [34]. CIE also proposed that the ratio of the illuminance of the working surface in the building space to the illuminance of the traffic space in the same space should not exceed 3:1, and the ratio of two adjacent rooms should not exceed 5:1 [35]. These two ratios play a crucial reference sway for the setting of illuminance. What we simulate in our experiments is the effect of the illuminance value of the light environment in the space of adjacent spaces on the comfort of human eyes. Therefore, the experimental illuminance values are set for illuminance variations of 1:3, 1:5, 3:1, and 5:1. Table 2 shows the data of 22 sets of working conditions.

Table 2. Data of experimental group.

Experimental Group	Starting Illuminance Value	Final Illuminance Value	Illuminance Ratio
1	100 lx ± 5 lx	300 lx ± 5 lx	1:3
2	30 lx ± 5 lx	90 lx ± 5 lx	1:3
3	1500 lx ± 5 lx	4500 lx ± 5 lx	1:3
4	1000 lx ± 5 lx	3000 lx ± 5 lx	1:3
5	500 lx ± 5 lx	1500 lx ± 5 lx	1:3
6	300 lx ± 5 lx	900 lx ± 5 lx	1:3
7	300 lx ± 5 lx	100 lx ± 5 lx	3:1
8	90 lx ± 5 lx	30 lx ± 5 lx	3:1
9	4500 lx ± 5 lx	1500 lx ± 5 lx	3:1
10	3000 lx ± 5 lx	1000 lx ± 5 lx	3:1
11	1500 lx ± 5 lx	500 lx ± 5 lx	3:1
12	900 lx ± 5 lx	300 lx ± 5 lx	3:1
13	100 lx ± 5 lx	500 lx ± 5 lx	1:5
14	500 lx ± 5 lx	2500 lx ± 5 lx	1:5
15	1000 lx ± 5 lx	5000 lx ± 5 lx	1:5
16	150 lx ± 5 lx	750 lx ± 5 lx	1:5
17	750 lx ± 5 lx	3750 lx ± 5 lx	1:5
18	500 lx ± 5 lx	100 lx ± 5 lx	5:1
19	2500 lx ± 5 lx	500 lx ± 5 lx	5:1
20	5000 lx ± 5 lx	1000 lx ± 5 lx	5:1
21	750 lx ± 5 lx	150 lx ± 5 lx	5:1
22	3750 lx ± 5 lx	750 lx ± 5 lx	5:1

3.3.4. Experimental Procedures

The experiments need to be conducted under optical darkroom conditions to ensure that the process is free of interference from external light. The vertical illuminance of the test board was selected as the only variable, controlling for other variables that remained constant.

A sample of 30 participants meeting the following requirements was selected to participate in the experiment by randomization: students and teachers aged 20–35 who worked in related fields, 15 males and 15 females, making a total of 30 people, with corrected visual acuity ≥ 5.0, other normal visual functions, and physical and mental health, and the list of participants was counted and recorded, and personal information such as age and gender of the participants was recorded one by one. We explained the contents of the experiment to the participants before the experiment and simulated the experimental process. Three experiments were conducted for each subject to ensure the accuracy of the experimental data. Subjective scale evaluation of the participants was required after each experiment. Under one condition, the reaction time and comfort score of one participant were averaged by three times of data.

A certain experiment time was determined, and the participant's initial heart rate was first measured and recorded before the participant started each set of experiments. To allow the participants to adapt to the light environment at the initial illuminance level, the participants were allowed to adapt to the light environment for different periods depending on the initial illuminance level before the experiments began, and the experimental test work was started after the participants believed that their eyes had fully adapted to this light environment and were stable. During the experiment, the participant's eyes should always be binocular and look at the Landolt ring test board. The specific experimental flow is shown in Figure 7.

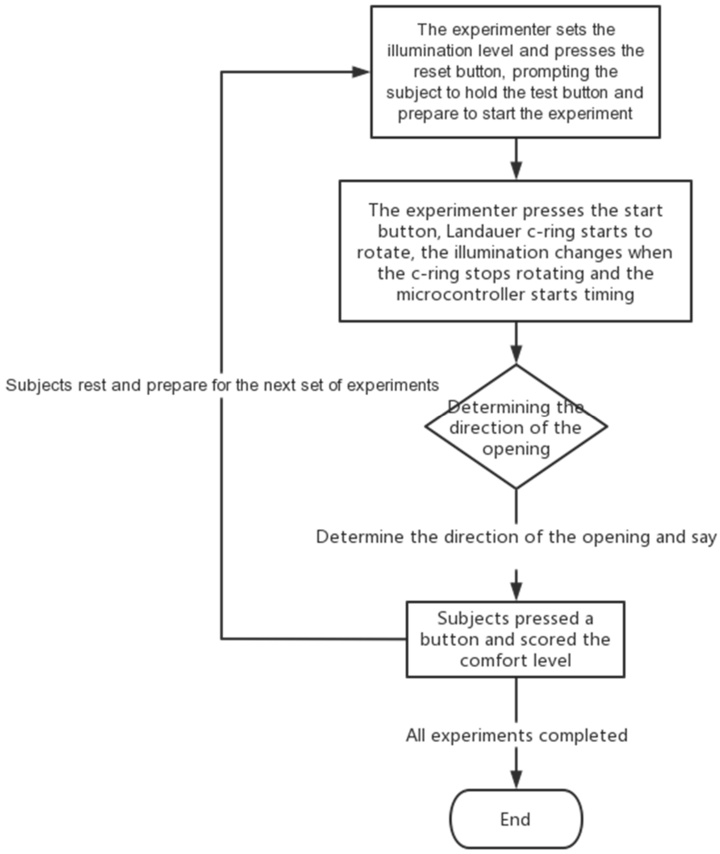


Figure 7. Experimental flow diagram.

During the experiment, the experimenter first presses the reset button to complete the cleanup of the last data, the control button to control the microcontroller to start, prompting the participant to hold the test button, and then carries out experimental testing work. The experimenter presses the start button; at this time the motor begins to drive the test board together, the rotation stops at the same time, the light switches, the illuminance in the space into another illuminance, and at the same time, the test board on the Landolt ring is fixed at a certain angle and triggers the microcontroller to enter the experimental timing program. After the switch in space, the participant observes the opening direction of "C" of the Landolt ring on the test board, and after the participant's eyes recognize it, he/she keeps his/her eyes fixed on the opening direction, and says the opening direction and presses the button. At this point, the microcontroller stops timing and uploads the single reaction time to the PC. After the experimenter determines that data entry has been completed, the participant is required to score and record the comfort level for this illuminance change and adjust the light source brightness to allow the participant to rest for 10 to 40 min to adapt to the environment before repeating the next set of experiments. After collecting sufficient test data, the experimental test is stopped. After completing the above work, the next experimental participant repeats this experimental process until the end of the experimental test. The photo of the experimental process is shown in Figure 8.

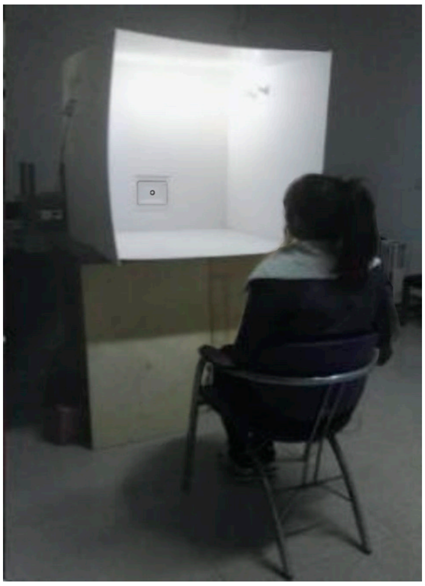


Figure 8. A photo of the experimental process.

4. Results

After the experiments were completed, we organized all the data. First, the data with large errors can be manually eliminated in the process of collation, and all of the data of the 20 groups of working conditions are integrated into one table. The SPSS software was used to analyze the data. Since the visual adaptation mechanism is different for increasing illuminance and decreasing illuminance [36], the data will be organized and analyzed separately into increasing and decreasing sets, and we have to correlate the data of reaction time with the data of comfort scoring in order to determine whether there is a real correlation between the subjectively scored comfort scores and the objectively experimentally derived reaction times. The color temperature measured in the actual experimental conditions is 4075 K, and the Duv value is 0.003 according to the calculation [37]. Some experimental data are shown in Table 3.

Table 3. Partial experimental data.

Experimental Group	Starting Illuminance Value	Final Illuminance Value	Reaction Time (s)	Comfort Score	The Difference in Illuminance Variation (lx)	Illuminance Ratio
1	98 lx ± 5 lx	301 lx ± 5 lx	0.647	1	−203	1:3
2	30 lx ± 5 lx	89 lx ± 5 lx	0.826	−1	−59	1:3
3	1497 lx ± 5 lx	4503 lx ± 5 lx	0.924	0	−3006	1:3
4	750 lx ± 5 lx	3747 lx ± 5 lx	0.656	2	−2997	1:5
5	98 lx ± 5 lx	502 lx ± 5 lx	0.783	1	−404	1:5
6	502 lx ± 5 lx	2505 lx ± 5 lx	0.95	−1	−2003	1:5
7	150 lx ± 5 lx	750 lx ± 5 lx	0.837	2	−600	1:5
8	30 lx ± 5 lx	98 lx ± 5 lx	0.647	1	68	3:1

4.1. Correlation Analysis Methods

The correlation analysis was performed using SPSS data analysis software to first assess the correlation of the sample variables. Common correlation analyses include Pearson correlation analysis and Spearman correlation analysis.

1. Pearson correlation analysis

If the *p* value of the *K* test or *S* test is greater than 0.05, Pearson correlation analysis can be carried out. If the results of the test are contradictory, the former is selected according to the principle of choosing the former when the sample size is small and the latter when the sample size is large, and a sample size greater than 50 belongs to large sample data. In addition, there are not very strict rules for normality, by looking at the Q–Q plot, histogram, and *p*–*p* plot of statistical data can also determine whether it is approximately normal, and Pearson correlation analysis can also be performed if it is approximately normal [38].

The closer the absolute value of Pearson correlation coefficient (*r* value) is to 1, the stronger the correlation is. The closer the r value is to 0, the weaker the correlation is. The range of values to determine the correlation between variables is generally as follows: the absolute value of r value is high-intensity correlation in the range of 0.7~1, strong correlation in the range of 0.5~0.7, and moderate correlation in the range of 0.3~0.5; 0 to 0.3 is weakly correlated or uncorrelated.

2. Spearman correlation analysis

Spearman correlation analysis can be applied when the bivariate does not conform to normal distribution or one of the variables does not conform to normal distribution.

4.2. Normality Test

For the data obtained from the experiment we need to perform correlation analysis, and to determine the method of correlation analysis, the first step is to perform a normal distribution test for the variables of reaction time and comfort score. Since the sample size was greater than 50 groups, the Kolmogorov–Smirnov test was used.

The significant *p*-value of reaction time under increasing illuminance is greater than 0.05, which is in line with normal distribution. The powers of all the tests considered in this study increase as the sample size and significance level increase [39]. Other factors and decreasing illumination conditions do not conform to a normal distribution, as shown in Tables 4 and 5. Therefore, Spearman correlation analysis can be applied to the factors under both increasing and decreasing illuminance conditions.

Table 4. Test for normality under increasing illuminance.

	Kolmogorov–Smirnov [a]		
	Statistic	**df**	**Sig.**
Reaction time	0.077	119	0.077
Comfort Score	0.177	119	0.000
Illuminance difference	0.293	119	0.000

a. Lilliefors Significance Correction.

Table 5. Test for normality under decreasing illuminance.

	Kolmogorov–Smirnova		
	Statistic	**df**	**Sig.**
Reaction time	0.108	141	0.000
Comfort Score	0.192	141	0.000
Illuminance difference	0.315	141	0.000

4.3. Correlation Analysis

From Table 6, it can be learned that under the condition of increasing illuminance, the data show that the correlation coefficient between reaction time and comfort score r = −0.510, which is significant at 0.001 and meets the requirement of less than 0.05, indicating that the correlation between reaction time and comfort score is real and high test standard, showing a moderate negative correlation, i.e., the visual comfort score gradually decreases as the reaction time increases.

Table 6. Correlation between reaction time and comfort under increasing illuminance.

			Reaction Time	Comfort Score	Illuminance Difference
Spearman Rho	Reaction time	correlation	1.000	−510 **	0.236 **
		Sig. (2-tailed)		0.000	0.010
		N	119	119	119
	1. Comfort Score	correlation	−510 **	1.000	−218 *
		Sig. (2-tailed)	0.000		0.017
		N	119	119	119
	2. Illuminance difference	correlation	0.236 **	−218 *	1.000
		Sig. (2-tailed)	0.010	0.017	
		N	119	119	119

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Under the condition of decreasing illuminance, the correlation coefficient between reaction time and comfort score can be obtained by Spearman correlation analysis, which is −0.527. Table 7 shows that reaction time is negatively correlated with comfort score.

Table 7. Spearman correlation under decreasing illuminance.

			Reaction Time	Comfort Score	Starting Illuminance
Spearman Rho	Reaction time	correlation	1.000	−527 **	−232 **
		Sig. (2-tailed)		0.000	0.006
		N	141	141	141
	Comfort score	correlation	−527 **	1.000	0.052
		Sig. (2-tailed)	0.000		0.544
		N	141	141	141
	Illuminance difference	correlation	−223 **	0.064	0.982 **
		Sig. (2-tailed)	0.008	0.448	0.000
		N	141	141	141
	Starting illuminance	correlation	−232 **	0.052	1.000
		Sig. (2-tailed)	0.006	0.544	
		N	141	141	141

**. Correlation is significant at the 0.01 level (2-tailed).

In summary, under both increasing and decreasing illuminance conditions, it was concluded that the reaction time showed a negative correlation with the comfort score. As the reaction time increases, the comfort level of human eyes decreases, the adaptation of human eyes has a negative correlation with comfort, and the reaction time can reflect the subjective comfort level of human eyes from an objective perspective.

5. Discussion

5.1. Effect of Gender on Visual Comfort

Through the comparison of the fitted curves of comfort scoring and reaction time for men and women, the mean comfort evaluation scores of men and women are not very different, and through the fitted curves, we can conclude that the reaction time is less than

0.96 s when the comfort score of men is greater than 0, while the reaction time is less than 1.03 s when the comfort score of female participants is greater than 0, as shown in Figure 9. The reaction time and comfort scoring curve trends of men and women are the same; it can be said that female reaction time is slightly longer than male reaction time, and that the requirement for comfort is lower in males; however, the difference is slight, indicating that gender has no significant effect on visual comfort. Ma Xiufeng et al. experimentally concluded that the trajectory of the average visual comfort curve for men and women almost overlaps [40], which is the same as the results of Ma Jian's experimental study [41].

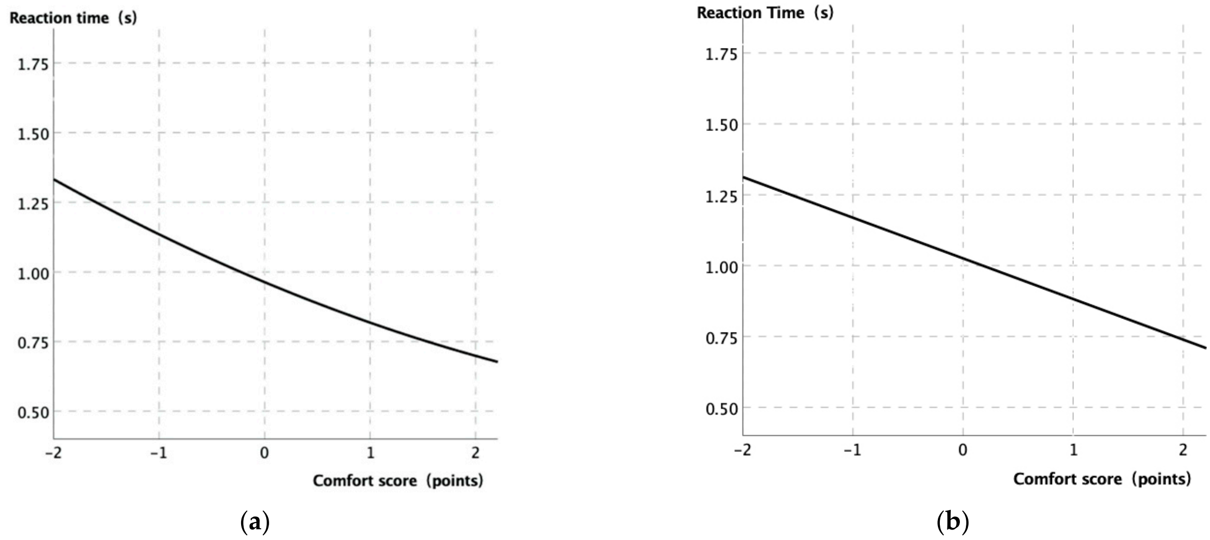


Figure 9. Regression curves of reaction time and comfort scores for men and women. (**a**)Regression curves of reaction time and comfort scores in men. (**b**) Regression curves of reaction time and comfort scores in women.

5.2. Effect of Starting Illuminance on Comfort Levels

The starting illuminance level in the experiment also affects the comfort score. We compared the experimental groups with starting illuminance of 100 lx, 500 lx, and 1000 lx. Figure 10 shows that the starting illuminance of 100 lx, 500 lx, and 1000 lx is more comfortable than the illuminance of 1:3 change. This means that the smaller the illuminance variation ratio, the higher the comfort level. In the 1:3 illuminance variation, the comfort scores of the 500 lx starting illuminance were better than those of the 1000 lx and 100 lx starting illuminance. The starting illuminance of 100 lx was the lowest under the 1:3 illuminance change process, probably because, although the participants were allowed to score the change process, the participants still unconsciously rated the comfort level lower in the darker change interval. Experiments by Tian Huijuan et al. also showed that vertical illuminance has an important effect on visual comfort and that too much or too little vertical illuminance can cause a certain level of discomfort [42].

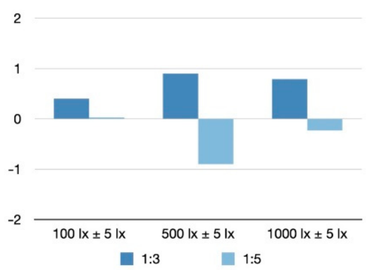


Figure 10. Histogram of starting illuminance and comfort scores.

Since the data on blood pressure and heart rate did not change significantly before and after the experiment, we can conclude that there is no significant effect on heart rate and blood pressure when the range of illuminance changes is within five times.

In addition, by analyzing the correlation data under increasing illuminance conditions, it is found that the larger the illuminance difference value, the larger the reaction time and the lower the comfort score. It means that the smaller the value of illuminance ratio in adjacent space, the higher the visual comfort level, the shorter the process of adaptation, and the higher the comfort level for changes. Therefore, in adjacent rooms, the smaller the illuminance ratio can ensure the comfort and health of users under the condition of meeting the values required by illumination standards.

Factors affecting the comfort of the human eye in the light environment include many aspects, although the illuminance of the light environment has a greater impact, the evaluation of comfort does not only include this one factor, but also ones such as color temperature, and other factors also have a greater impact on the light environment of the building space. In the future, when studying the changing light environment in depth, besides illumination, other factors, such as color temperature and spectrum, should be considered. To analyze the light environment parameters multivariate, the conclusions obtained can be more instructive.

5.3. Experimental Error Analysis

The experimental errors due to the inevitable errors of the experimental instruments and the individual differences of the participants and other such possible errors cannot be accounted for, but the errors generated by human operations can be eliminated. There are several common sources of error as follows.

5.3.1. Practice Effect

Sometimes the increase or decrease in experimental performance, such as reaction time, is caused by too many repetitions. We had to consider the effect of the practice effect in the experimental results. To minimize the effect of external factors on reaction time, experimental participants rested or chatted in a rest space after completing a set of experiments, thus avoiding or reducing the error from this effect.

5.3.2. Systematic Error

Systematic error is an error related to the measurement or other causes of variability from the true value. In the experiment, the reaction time is the sum of the reaction time of the human eye and the reaction time of the body, from the time the human eye recognizes and the brain sends a command to the time the button is pressed. Specifically, it is the time between the human eye recognizing the information about the direction of the Landolt ring, transmitting the signal to the brain, and then to the control hand pressing the button. Although the data can vary greatly between individuals, the differences between individuals can be neglected as systematic errors if only the whole is considered.

5.3.3. Behavioral Errors

There are two main reasons for the generation: one is the error due to the carelessness of the experimenter and the differences in factors such as wrong operation, wrong recording, wrong reading, etc. The second is due to the wrong reaction of the participant, such as untimely key presses, misjudgment of the opening direction of the Landolt ring, etc. If the participant misjudged the Landolt ring in the experiment, the experimental data of the current time was not uploaded and the current experiment was conducted again. Therefore, the number of experiments was increased in the experiment, and each group of experiments was conducted three times to take the average, and we can find that there is almost no difference in comfort score under the same illuminance change condition.

6. Conclusions

1. The human eye is an organ that receives light stimuli directly, so the visual adaptation time greatly affects visual comfort. The experimental study of visual adaptation and comfort combines the experimental method of subjective evaluation and objective measurement, which has the advantages of easy operation and analysis of subjective evaluation and the advantage of accurate objective measurement data. The conclusion that reaction time and subjective comfort score are negatively correlated under the condition that vertical illuminance is a single variable is drawn from the experiment, which means that visual comfort increases with the increase in reaction time, and reaction time can objectively reflect visual comfort.
2. Through the comparison of the fitted curves of comfort scoring and reaction time for men and women, the mean comfort evaluation scores of men and women are not very different, and through the fitted curves, we can conclude that the reaction time is less than 0.96 s when the comfort score of men is greater than 0; while the reaction time is less than 1.03 s, when the comfort score of female participants is greater than 0. The reaction time and comfort scoring curve trends of men and women are the same; it can be said that female reaction time is slightly longer than male or the requirement for comfort is lower than male, but the difference is slight, indicating that gender has no significant effect on visual comfort.
3. The data on blood pressure and heart rate did not change significantly before and after the experiment; we can conclude that there is no significant effect on blood pressure and heart rate when the range of illuminance changes within five times.
4. In addition, too little vertical illuminance can cause a certain level of discomfort, so that the greater the illuminance difference, the greater the reaction time and the lower the comfort score, and controlling the illuminance ratio of adjacent spaces can ensure health and comfort. When comparing experimental groups with starting illuminances of 100 lx, 500 lx, and 1000 lx, it was found that the illuminance 1:3 change condition was more comfortable than the illuminance 1:5 change regardless of the starting illuminance, indicating that the smaller the illuminance change ratio the higher the comfort level, while the 500 lx starting illuminance scored better than the 1000 lx and 100 lx starting illuminance in the illuminance 1:3 change. When the initial illumination is 100 lx, the comfort is the lowest. We think that in the dark change interval, participants unconsciously score not only the change interval, but also the light environment. This study provides data reference for improving the light comfort of architectural space and creates a more comfortable and healthier light environment for people.

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