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Research on work efficiency and light comfort based on EEG evaluation method

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A R T I C L E I N F O

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A B S T R A C T

The indoor light environment is known to significantly affect the performance, emotions, and physical and mental health of the working staff; therefore, improving the working environment can augment their working efficiency. In this study, the results of the subjective, task, and physiological evaluations of personnel under different combinations of five illumination levels (75 lx, 100 lx, 200 lx, 300 lx, 500 lx) and three colour temperatures (3000 K, 4000 K, 6000 K) have been analysed. The subjective evaluation shows that illumination has a highly significant influence on the perception of brightness, colour authenticity, spaciousness, fatigue, and relaxation, whereas colour temperature only affects the perception of spaciousness. Improving the illumination of the work environment within the scope of the study has been observed to help in improving the light comfort, but with a declining trend. The task evaluation showed that colour temperature is a significant factor that affects the reading efficiency, which is generally improved using a neutral colour temperature. The physiological evaluation indicated that illumination significantly affects the response of the visual centre. A comprehensive light comfort zone is suggested based on this research, which could be a valuable reference for designing the indoor light environments and improving the satisfaction associated with the light environment.

1. Introduction

With the social development and changes in the nature of work, the quality of the indoor environment has a significant impact on the health and work efficiency of the staff [1–3]. Woods et al. showed that improving the indoor office environment can increase the work efficiency by 18%, and a 1% increase in staff efficiency can make up for the operation and maintenance costs of the building [4]. The study by Yang [5] found that the human body receives 87% of its information from the outside world through vision; therefore, the quality of the light environment directly affects the reception and processing of information and indirectly affects visual fatigue, work efficiency, and emotional changes as well as other concerns [6].

There are numerous complicated parameters influencing the light environment. Therefore, illumination continues to be the primary visual attribute for designing practical lighting environments. There is no uniform quantitative standard for illumination values in office buildings. The British Institute of Lighting Engineering recommends 500 lx for offices where typing is carried out occasionally and 750 lx for offices where design and typing are the daily routine. In Japan, the illumination of ordinary offices is required to be in the range of 500–750 lx, and according to the "Lighting of Indoor Workplace" of CIE, the average illumination of offices for writing, typing, reading, and data processing should be no less than 500 lx [7]. China's GB50034-2013 "Architectural Lighting Design Standards" stipulates that the average illumination of the work space in an ordinary office should not be less than 300 lx [8].

Numerous studies have shown that the light environment directly affects work performance through visual effects and indirectly affects the attention, arousal level, and work enthusiasm of the people. Studies by Grünberger et al. [9] have shown that the concentration level of staff working with an environmental illumination of 2500 lx is significantly higher than with 500 lx. Cajochen [10] concluded that strong light can increase alertness and reduce drowsiness. Studies by Shinomura et al. [11] have shown that sleepiness was more significant in subjects under a low colour temperature than a high colour temperature. Additionally, tension, alertness, and concentration were higher in subjects under a high colour temperature than a low colour temperature, suggesting that brain excitability increased with the increase in the colour temperature of the light source. Tanabe and Nishihara [12] studied the effects of illumination on additional tasks and fatigue. The results showed that

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fatigue in the extreme environment of 3 lx increased, but the additional tasks were not affected. Tomoaki et al. [13] found that light sources with higher colour temperatures may affect sleep quality.

Manav [14] studied the influence of illumination and colour temperature on the staff and demonstrated that the performance of 2000 lx illumination for the impressions of comfort, spaciousness, brightness, and saturation evaluation was superior to that of 500 lx. Additionally, the colour temperature of 4000 K generated better impressions of comfort and spaciousness than at 2700 K, while 2700 K produced more relaxation and saturation evaluation than at 4000 K. The study [15] of Lan showed that for text and graphic deductive reasoning tasks, the performance at 300 lx was much higher than that at 50 lx and 3000 lx, and the performance of non-deductive reasoning tasks improved with increasing the illumination. However, the fatigue level of the staff in the high-illumination environment also increased significantly. Shamsul et al. [16] indicated that the participants preferred 4000 K and expected to work comfortably for more than 6 h. In study [17], the observers preferred 4000 K to 6500 K at a light level of 500 lx [18].

Studies have also shown that lighting can partially compensate for thermal discomfort by achieving a higher perceived visual comfort. Therefore, changes in colour temperature may indirectly affect light comfort through its effects on thermal comfort. Yang and Moon suggested [19] that visual comfort is not only affected by illumination but also by acoustic and thermal factors. However, the influence of illumination on visual comfort is less than the influence of temperature on thermal comfort or the influence of sound type and sound level on acoustic comfort. Yu and Akita established [20] that higher correlated colour temperatures (CCT) were associated with higher spatial brightness, and lower CCTs were associated with a higher sense of security, restfulness, and positive feelings. Huang et al. discovered [21] that the subjects had the greatest capability for colour discrimination and the highest rating for colour preference under the colour temperature of 5500 K. Christian et al. conducted an interesting experiment [22] in an environment of constant warm light with a maintained correlated colour temperature average of 2900 K and lighting level of 450 lx to a dynamic cool light of 4900 K and 750 lx, combined with a high ventilation rate, where the processing speed, concentration and math skills of pupils enhanced significantly. The above research on light environment and comfort focuses on the statistical application of subjective feelings but lacks objective and passive indicators.

Electroencephalograms (EEGs) have been used extensively with subjective sensory and cognitive tasks, suggesting that an EEG can be beneficial as an objective indicator to support traditional subjective and task evaluation methods [23]. Srinivasan discovered that the spectral characteristics of an EEG can be used to predict attention levels [24]. EEG studies have demonstrated that at the illumination level of 1700 lx, delta waves affecting the sleepiness level were significantly less than at the illumination level of 450 lx, indicating that a strong light can improve the alertness of the central nervous system [25]. The study of Eroğlu et al. [26] suggested that the types and brightness of stimulus images are related to the average response levels in the parietal and occipital regions. Michal et al. [27] proved that blue (short-wavelength) light is more distressing than long-wavelength light. Additionally Jan et al. [28], reported that optimizing the spectrum is crucial to improving daytime alertness, and [29,30] suggested that the effects of light conditions on alertness varies throughout the day. Table 1 provides the experimental conditions and fundamental conclusions of the relevant studies.

The current study comprehensively considered subjective feelings and objective physiological indicators and applied visual evoked potential testing to evaluate the light environment, unifying subjective initiatives with objective regularity and filling the gaps in research.

Table 1
Conclusions of relative studies.

Researcher	Subjects	Illumination/lx	Colour temperature/K	Results
Grünberger [8]	8 male + 7 female	500, 2500	–	Illumination affects attention
Manav [14]	56 subjects	500, 750, 1000, 2000	2700, 4000	Illumination and colour temperature affect subjective indices
Lan [15]	7 male + 1 female	50, 300, 3000	–	Illumination affects task performance and fatigue
Marije et al. [18]	35 subjects	5, 1200	2700, 5800	Lighting can partially compensate for thermal discomfort
Yang and Moon [19]	30 male + 30 female	100, 500, 1000	–	Sound and heat affect visual comfort
Yu and Akita [20]	15 male + 3 female	150, 300	2800, 5,000, 6700	Security was significantly influenced by CCT rather than illumination
Huang et al. [21]	42 subjects	200	2500–6500	Colour temperature affects colour recognition

2. Experimental methodology

2.1. Experimental conditions

The purpose of this experiment is to study the effects of illumination and colour temperature of the indoor lighting environment on the light comfort, visual fatigue, and work efficiency of humans. The following are the illumination and colour temperature parameters.

Illumination is defined as the energy of visible light received per unit area. A sensible illumination design is of great significance for increasing subjective comfort, reducing visual fatigue, improving work efficiency, and reducing energy consumption in buildings. Because the minimum difference in illumination that can be distinguished by subjective human perception is approximately 1.5 times, it has been stipulated that the stable average illumination values on the working surface in China are (ranging from low to high) 0.5, 1, 3, 5, 10, 15, 20, 30, 50, 75, 100, 150, 200, 300, 500, 750, 1,000, 1,500, 2,000, 3,000, and 5000 lx. Table 2 [8] shows the design parameters of the lighting environment for office buildings specified in the China Architectural Lighting Design Standard GB50034-2013.

The research on the satisfaction of the office light environment has indicated that with the increase in illumination, the satisfaction of the staff initially increases but then decreases, with a relatively high

Table 2
Office building lighting design standard value.

Venue	Plane or height	Illumination standard/lx	UGR	U_0	R_a
Ordinary office	0.75 m Plane	300	19	0.6	80
Executive office	0.75 m Plane	500	19	0.6	80
Board room	0.75 m Plane	300	19	0.6	80
Video conference room	0.75 m Plane	500	19	0.6	80
Design room	Working face	300	19	0.6	80

UGR, Unified Glare Rating; U_0, Illumination uniformity; R_a, colour rendering index.

illumination interval of satisfaction. Yu et al. studied the effects of illumination levels on vision and found that when the illumination was within the range of 1.7–2160 lx, enhancing the illumination would improve visual perception. However, with the continuous increase in illumination, such improvement would lessen, showing a "law of diminishing returns" [31]. Based on the above specifications and research results, five illumination levels of 75, 100, 200, 300, and 500 lx were set for this experiment.

Colour temperature is the unit of measurement of the colour component of light. Different light sources have different luminescent materials, with varying spectral energy distributions. A blackbody after being heated gradually turns red, yellow, white, and blue. When it is heated to a specific temperature, the spectral component of the light emitted by the blackbody is the colour temperature at that particular temperature. Because the subjective feelings of the human body are not the same under different wavelengths of light, the colour temperature also plays an important role in the light comfort of the human body. For example, among two bulbs of the same power, the one with the higher colour temperature is observed to be brighter. "Architectural Lighting Design Standard GB50034-2013" explains that the colour temperatures of indoor lighting sources are divided into three groups, namely: warm, medium, and cool; the specific groupings are shown in Table 3 [8].

Three colour temperature levels of 6,000, 4,000, and 3000 K were used in this study to make them distinguishable. Table 4 lists the variables and parameters in the experiment.

2.2. Experimental chamber

The experiment was carried out in a closed chamber with white walls at regulated temperature and humidity for simulating an ordinary office. On the ceiling, there were six equally spaced lamps of adjustable illumination and colour temperature, and there was no other light source except the computer display screen. The temperature was controlled at an accuracy of ±0.5 °C, and the humidity at ±5% through a perforated ceiling air supply by the air conditioning system. The experimental instruments and equipment were placed on the desk at a height of 0.75 m. Please see Fig. 1 for the floor plan of the equipment and lamps.

2.3. Subjects

In order to simulate the actual office staff, certain conditions were set for the selection of the subjects, including good health, adequate reading and cognitive skills, and normal vision, with or without wearing corrective lenses. The subjects of this experiment consisted of 18 office workers (10 males and 8 females) aged between 23 and 26; they were in good health, with visual acuity no less than 5.0 on the standard logarithmic visual acuity chart after optical correction and the visual acuity correction degree of less than 400°. The basic information of the subjects is shown in Table 5.

To avoid influencing the experiment, the subjects were required to sufficiently rest and demonstrate emotional stability before the experiment, avoid significant mood swings, refrain from consuming alcohol for 12 h and smoking for 8 h, and avoid consuming beverages such as coffee or energy drinks that would have an irritant effect on the body. In addition, they were required to avoid strenuous exercises within 3 h to ensure that their blood glucose levels remained stable and normal and prevent them from being too excited or tired.

The experiment was conducted using the order of Latin Squares (Table 6) with a total of 15 working conditions and 9 test groups, each with 2 people to avoid the influence of cumulative visual fatigue on the experimental results that could be caused by experimental disorder.

Table 3
Examples of correlated colour temperature and application sites.

Colour grouping	Colour feature	Correlated colour temperature/K	Examples of application sites
I	Warm	<3300	Guest room, bedroom, ward, bar, restaurant
II	Medium	3300–5300	Office, classroom, reading room, shopping mall, clinic, laboratory
III	Cool	>5300	Hot processing workshop, high illumination place

Table 4
Variables and parameters in the experiment.

Condition number	Illumination/lx	Colour temperature/K
1	75	6000
2	100	
3	200	
4	300	
5	500	
6	75	4000
7	100	
8	200	
9	300	
10	500	
11	75	3000
12	100	
13	200	
14	300	
15	500	

2.4. Experimental contents

2.4.1. Physical measurement

An environment that is either too cold or too hot will affect the work performance [32]. In order to avoid the influence of human thermal sensation differences on the experiment, it was necessary to ensure that the subjects were in the thermal comfort range. Therefore, the temperature and relative humidity of the experimental conditions were determined within the temperature and humidity range corresponding to Ref. $PMV \in (-0.5, +0.5)$ [33]. The clothing insulation of the subjects was set at 0.73 clo, and the indoor air speed was set at 0.06 m/s. The subjects were in a sitting position, avoiding mechanical work, and assumed to have a metabolic level of 1.0 MET. The calculated comfortable temperature range was 23–25.8 °C, and the relative humidity range was 55–65%. See Table 7 for the thermal environment parameters.

2.4.2. Subjective evaluation

The satisfaction of the light environment under the current working conditions was evaluated from five perspectives: brightness, colour authenticity, spaciousness, fatigue, and relaxation. Brightness refers to the ratio of the light intensity of the luminous body to the area of the light source perceived by the human eye, and is defined as the unit brightness of the light source, that is, the luminous intensity per unit projected area, or candela per square meter (cd/m^2). The brightness is a subjective indicator of how people feel about the intensity of the light. Colour authenticity is measured by colour rendering; when light sources of different spectra shine on objects of the same colour, the characteristics of different colours appear (i.e., the degree of fidelity of the colours). There is no strict definition of spaciousness, which is a subjective indicator, and a low sense of spaciousness indicates a high degree of depression.

The evaluation scale refers to the five-point index of the ISO10551 standard for tolerance scale [34]. The five-point scale is also used in the articles by Velt and Daanen [35] and Guan et al. [36]. On this basis, we have made a little change, with a negative value to mark unacceptable, following the scoring rules: unbearable (−4), extremely uncomfortable (−3), uncomfortable (−2), slightly uncomfortable (−1), and comfortable (0), maintaining one decimal place. This will make the subject feel

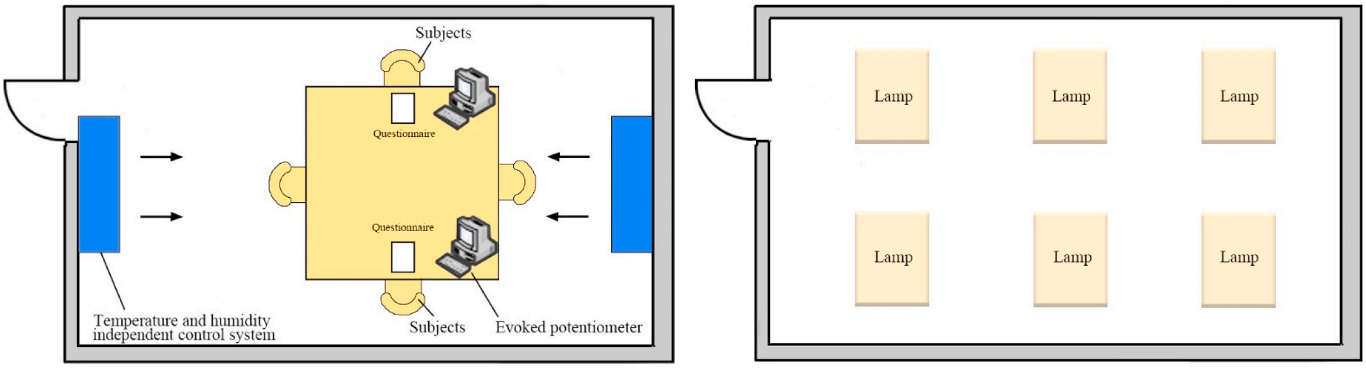

Fig. 1. Floor plan of the equipment and lamps.

Table 5
Basic information of the subjects.

	Male	Female	Total
Age			
Max	26	25	26
Min	22	22	22
Average	23.9	23.3	23.6
Vision correction			
Yes	9	5	14
No	1	3	4

Time of experiment: 8:30 a.m.–12:00 a.m., 2:30 p.m.–5:00 p.m.

more intuitive. The evaluation scale is shown in Fig. 2.

2.4.3. Task evaluation

The task evaluation method was used to directly analyse the work efficiency by performing a task with high credibility and was the basis for determining the quantitative relationship between indoor illumination, colour temperature, and work efficiency [37]. Pointer tables were adopted as test materials in the experiment to evaluate reading efficiency according to the design process in Fig. 3. The advantage of this method is that the difficulty of each test is consistent, and the test results are convenient for subsequent analysis and quantitative processing.

Each material consists of 160 pointer patterns, including arrows in eight directions: up, down, left, right, upper left, lower left, upper right, and lower right. The only difference between the patterns is the arrow directions, with the arrows in each direction appearing 20 times and are neatly arranged in a 10 × 16 table. Before the test, two target arrows in different directions were randomly assigned, the arrows in the same condition being assigned the same direction. The subjects were required to draw the specified arrows as quickly and accurately as possible without rechecking during the entire test, and the time consumed was recorded. All the arrows that were wrongly selected, multiple-selected, or missed were judged as wrong. The test materials of the pointer table are shown in Fig. 4.

2.4.4. Physiological evaluation

For the clinical testing, pattern reversal visual evoked potential (PRVEP) was used to test the electrical activity on the occipital visual cortex evoked by the stimulation of the patterns on the retina, which is an important means to study sensory functions, nervous system diseases, behaviour, and psychological activities [38,39].

According to the 10–20 systematic electrode placement method prescribed by the International Electroencephalography Society, the FPz was located at 10% of the distance from the nasal root to the back of the head, and an electrode was located every 20% of the total distance from the FPz, which are Fz, Cz, Pz, and Oz respectively, and the spacing between Oz and the external occipital protuberance is 10% of the total distance. For the test, Fz was the reference electrode, Oz was the action electrode, and the grounding electrode was placed on the centre of the forehead. The electrode positions are shown in Fig. 5.

When measuring the PRVEP, the bipolar lead method was mostly adopted, where only two active electrodes were used on the scalp, eliminating any irrelevant electrodes. The advantage of this method is that the differences in the EEG measurements between the two electrodes is recorded, which can greatly reduce the interference and eliminate errors caused by irrelevant electrodes. However, it was necessary to ensure that the distance of the two active electrodes is more than 3 cm to avoid the potential differences offsetting each other. Furthermore, a conductive paste was used to ensure that the electrodes had good contact with the skin. The test was started only after the impedance had dropped below 15 kΩ.

The evoked potentiometer used the binocular visual evoked potential test, and the stimulus form was an 8 × 6 pattern reversal, as shown in Fig. 6. At the beginning of the test, the black and white checkerboard grids alternated at a frequency of 1.5 Hz, and 900 data were collected for each stimulus at sampling intervals of 0.5 m and were superimposed 150 times to eliminate the interference of irrelevant electrical signals. The sampling upper limit was set at 100 Hz, and the measured data had gone through a low-pass filter.

The subjects' eyes were kept level with the screen that was 0.6 m away, focusing on the red cross in the centre of the screen throughout the test. They sat with their bodies relaxed and wore a headset before the test to avoid the influence of muscle tension and sound on the test results.

A flash fusion frequency meter was used to test the maximum flashing frequency that could be distinguished by human eyes. The subjects stared at the light flashing at a fixed frequency inside the instrument, and the flashing frequency was gradually increased. When the subjects observed that the flashing had stopped, the critical value was recorded. The higher the test value, the higher the discernible blink frequency and eye acuity, and the smaller the degree of visual fatigue; conversely, the smaller the test value, the lower the acuity of the eyes and the greater the degree of visual fatigue.

2.5. Test procedure

Before the test, the subjects changed into the experimental clothes in the preparation room. After entering the laboratory, they were required to sit quietly in the experimental lighting environment for 10 min, during which they read the paper books provided to them and were prohibited from using electronic devices such as mobile phones. After the adaptation period, the subjects were required to fill in a questionnaire according to their subjective feelings towards the light environment and then underwent a reading efficiency test. After the completion of each group of two subjects, the experimenter connected the electrodes and wires to the subjects and helped put earphones on them to conduct the combined frequency test of the visual evoked potential and flashes. At the end of each session, the subjects closed their eyes or looked off in

Table 6
Experimental order.

Group Number / Condition Number / Experimental order	A	B	C	D	E	F	G	H	I
1	1	2	3	4	5	6	7	8	9
2	2	3	4	5	6	7	8	9	10
3	3	4	5	6	7	8	9	10	11
4	4	5	6	7	8	9	10	11	12
5	5	6	7	8	9	10	11	12	13
6	6	7	8	9	10	11	12	13	14
7	7	8	9	10	11	12	13	14	15
8	8	9	10	11	12	13	14	15	1
9	9	10	11	12	13	14	15	1	2
10	10	11	12	13	14	15	1	2	3
11	11	12	13	14	15	1	2	3	4
12	12	13	14	15	1	2	3	4	5
13	13	14	15	1	2	3	4	5	6
14	14	15	1	2	3	4	5	6	7
15	15	1	2	3	4	5	6	7	8

Table 7
Environmental parameters.

Parameters	Temperature/°C	Relative humidity/%	Air speed/(m s^{-1})
Set value	24 ± 0.5	60 ± 5	0.06

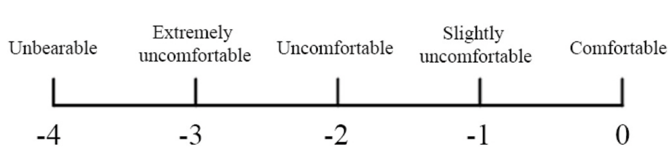

Fig. 2. Evaluation scale.

the distance for 5 min. Each group of subjects was continuously tested for three working sessions. The experimental process is shown in Fig. 7.

2.6. Statistical analysis

2.6.1. The method of determining the weight of entropy

The method of determining the weight of entropy was adopted to calculate the weight of the five subjective evaluation indices: brightness, colour authenticity, spaciousness, fatigue, and relaxation. Firstly, all the results were normalized according to Equation (1) to obtain the normalized matrix $\mathrm{Y} = \{y_{ij}\}_{m \times n}$, then, the information entropy value of each indicator was calculated according to Equation (2); the information utility value h_j and information entropy value e_j satisfy Equation (3). After the relativization of the information utility value (Equation (4)),

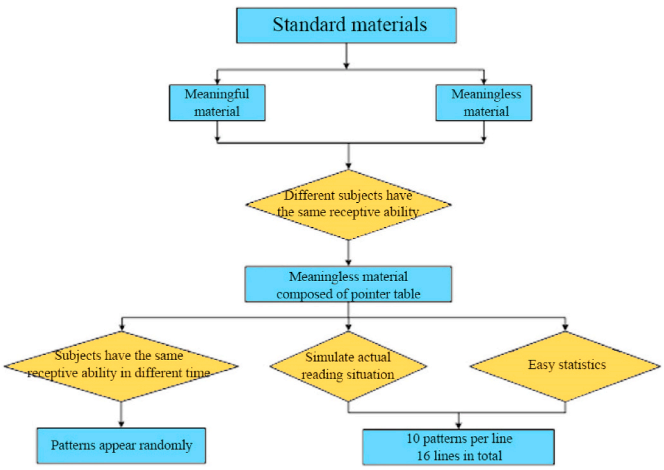

Fig. 3. Pointer table design process.

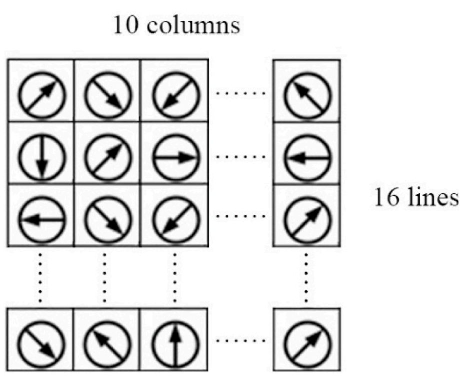

Fig. 4. Test materials of pointer table.

the weight of each indicator could be obtained.

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \ 0 \le y_{ij} \le 1 \tag{1}$$

$$e_j = -k \sum_{i=1}^{m} y_{ij} ln y_{ij} \tag{2}$$

$$h_j = 1 - e_j \tag{3}$$

$$w_j = \frac{h_j}{\sum_{j=1}^{n} h_j} \tag{4}$$

where coefficient k is related to sample number m. In a system with absolutely disordered information, the maximum entropy value occurs when $y_{ij} = \frac{1}{m}$, that is, $e = 1$. Substituting it e into Equation (2), the relationship between k and sample size m could be obtained, as shown in Equations (5) and (6).

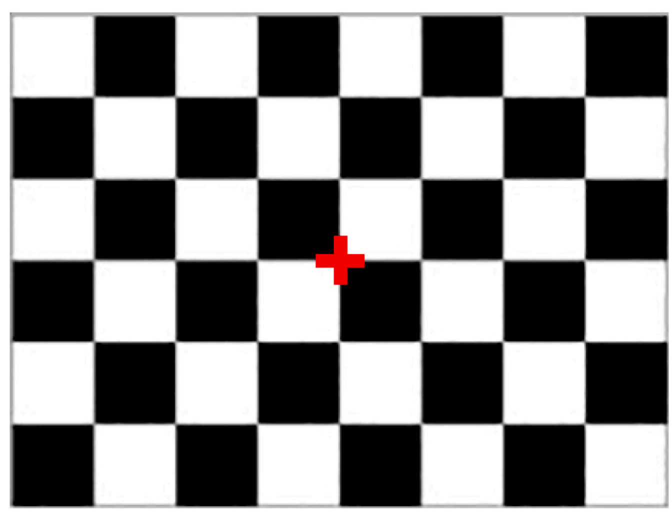

Fig. 6. PRVEP stimulation image.

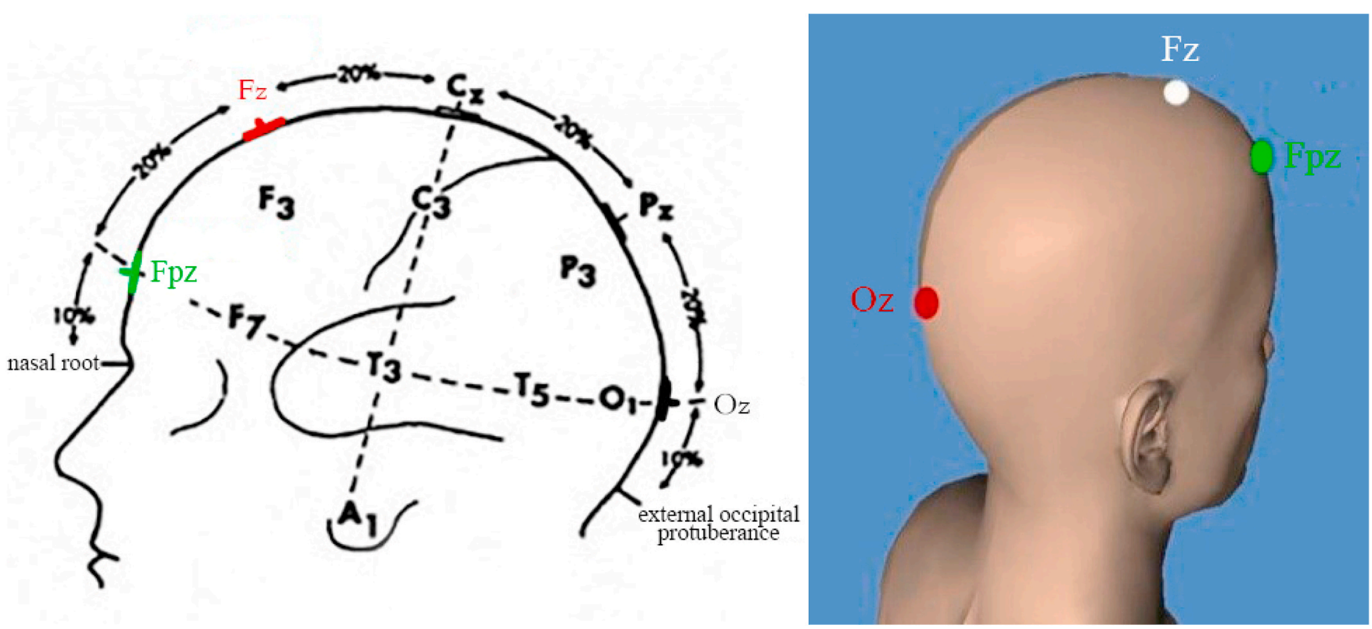

Fig. 5. Electrode positions.

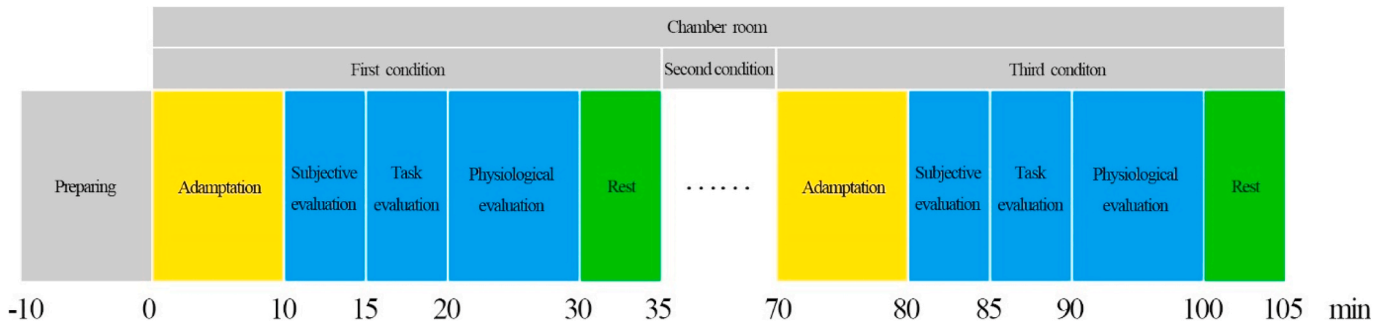

Fig. 7. Experimental process.

$$e = -k\sum_{i=1}^{m}\frac{1}{m}ln\frac{1}{m} = k\sum_{i=1}^{m}\frac{1}{m}lnm = klnm = 1 \quad (5)$$

$$k = (lnm)^{-1}, 0 \le e \le 1 \quad (6)$$

2.6.2. *Relative reading time*

In order to comprehensively consider the two factors of test time and accuracy for the pointer table, the concept of equivalent time was introduced. The equivalent time for each test paper was calculated according to Equation (7), accuracy = (160 − number of errors)/160 × 100%.

$$T_e = \frac{T_a}{\eta} \quad (7)$$

where T_e = equivalent time, T_a = time consumed, and η = accuracy.

It was assumed that the subjects' reading level remained the same during the experiment, and the difficulty of the questionnaire did not change, so the relative time (Equation (8)) was used to represent the performance of a subject's task evaluation under a certain condition.

$$T_r = \overline{T_e} - T_e \quad (8)$$

where T_r = relative time and $\overline{T_e}$ = mean equivalent time under all working conditions for a subject.

2.6.3. *P_{100} relative value of latent period*

The checkerboard pattern reversal stimulation was characterized by a stable waveform and high repeatability. The image contained three waveform poles, N_{75}, P_{100}, and N_{145}, as shown in Fig. 8. Among them, the P_{100} latent period was defined as the time from the start of stimulation to the positive peak near 100 m. The peak of the P_{100} wave was the most obvious and stable, and the latent period showed little variability for an individual or between the individuals, which reflects the response speed of the sum of the post-synaptic potentials of the cerebral cortex neurons to the graphic stimulus, a common index for clinical diagnosis. Therefore, in this study, the P_{100} latent period at the level of 75 lx was taken as the standard value, and the standard value at the same colour temperature level was subtracted from the actual value of a working condition as the relative value, P_r, of the P_{100} latent period to describe the relationship between the response speed, illumination, and colour temperature. When this value is positive, indicating that the P_{100} latent period is greater than the standard value, the rate of visual information transmission is relatively slow, and the working efficiency is low. On the contrary, when the latent period of P_{100} is smaller than the standard value, the rate of visual information transmission is relatively fast, and the working efficiency is high.

3. Results

3.1. *Subjective evaluation*

The method of determining the weight of entropy was used to

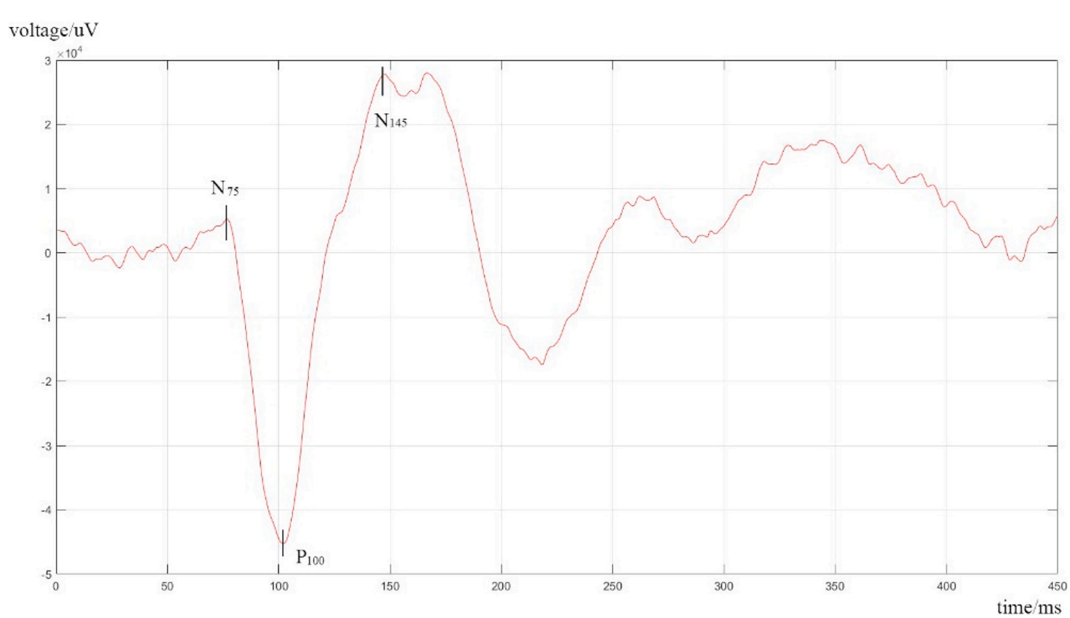

Fig. 8. PRVEP image.

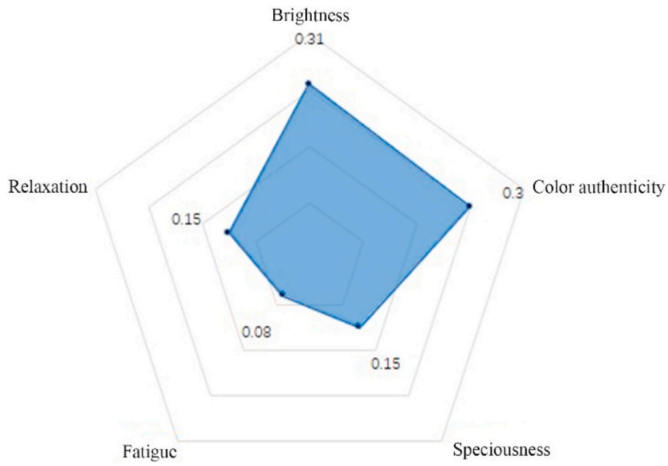

Fig. 9. Weight of five indicators.

calculate the weight of the five indicators in the questionnaire: brightness, colour authenticity, spaciousness, fatigue, and relaxation, as shown in Fig. 9. The results show that brightness and colour authenticity have a relatively high influence on the subjective light comfort. The relationships between the score of the five indices under each working condition after a weighted sum and the illumination and colour temperature are shown in Fig. 10.

As can be seen in Fig. 10, the comprehensive subjective evaluation scores of cool, warm, and medium colour temperatures all increased with the increase in the average illumination of the working face, indicating that the improvement in the average illumination of the working face within the research scope is conducive to increasing the overall subjective comfort of the staff regarding the indoor light environment. However, when the illumination of the light with a colour temperature of 6000 K was increased from 300 lx to 500 lx, the comprehensive score of the subjective evaluation did not increase significantly, indicating that at this stage, there was little improvement in subjective comfort.

A significance analysis was conducted for the five subjective evaluation indices with the illumination and colour temperature, respectively. Among the five indices, illumination remained as a highly significant influencing factor, while colour temperature was a significant factor for only for the sense of spaciousness. The results are shown in Tables 8–12.

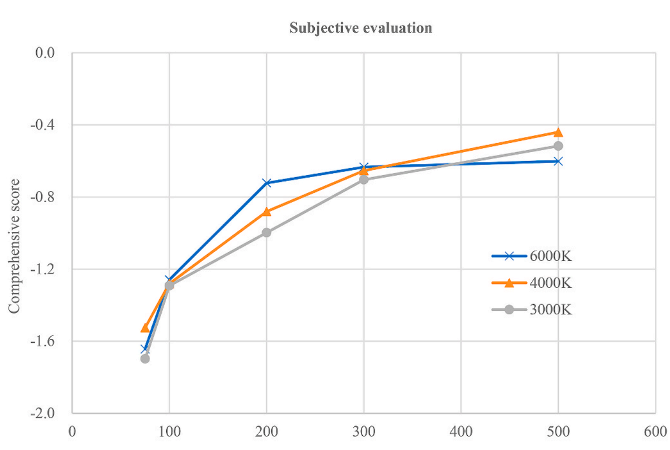

Fig. 10. The relationship of comprehensive score and illumination and CCT.

Table 8
Significance analysis results (brightness).

	Sum of squared deviations	df	Variance	F	Sig.
CCT	0.06004	2	0.03002	3.8348	Not significant
Illumination	4.7027	4	1.1757	150.18	Highly significant

Table 9
Significance analysis results (color authenticity).

	Sum of squared deviations	df	Variance	F	Sig.
CCT	0.017653	2	0.0088267	0.6136	Not significant
Illumination	2.6312	4	0.65781	45.729	Highly significant

Table 10
Significance analysis results (spaciousness).

	Sum of squared deviations	df	Variance	F	Sig.
CCT	0.044213	2	0.022107	4.5596	Significant
Illumination	1.9265	4	0.48163	99.34	Highly significant

Table 11
Significance analysis results (fatigue).

	Sum of squared deviations	df	Variance	F	Sig.
CCT	0.00988	2	0.00494	0.23704	Not significant
Illumination	1.0032	4	0.25079	12.034	Highly significant

Table 12
Significance analysis results (relaxation).

	Sum of squared deviations	df	Variance	F	Sig.
CCT	0.00976	2	0.00488	0.38817	Not significant
Illumination	0.74167	4	0.18542	14.749	Highly significant

Table 13
The results of One-way ANOVA (T_a).

	Type III square sum	df	Mean square	F	Sig.
Illumination	772.822	2	386.411	1.605	0.204
CCT	2605.502	4	651.376	2.705	0.032
Illumination × CCT	6344.232	8	793.029	3.293	0.002

3.2. Task evaluation

The results of the one-way analysis of variance for the actual reading time T_a are shown in Table 13. The results show that the colour temperature individually was a significant factor of T_a, and the interaction of illumination and colour temperature was highly significant for T_a. The relationship between T_r and illumination and colour temperature is shown in Fig. 11. As can be seen from the figure, under the 3000 K light, T_r always fluctuated around 0 s, and the influence of illumination on the

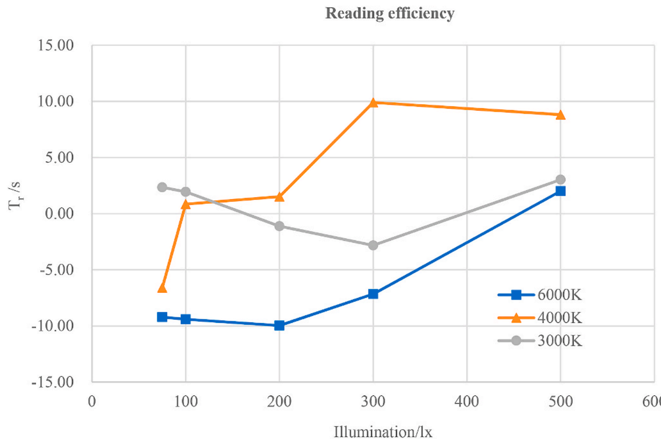

Fig. 11. The relationship between T_r and illumination and CCT.

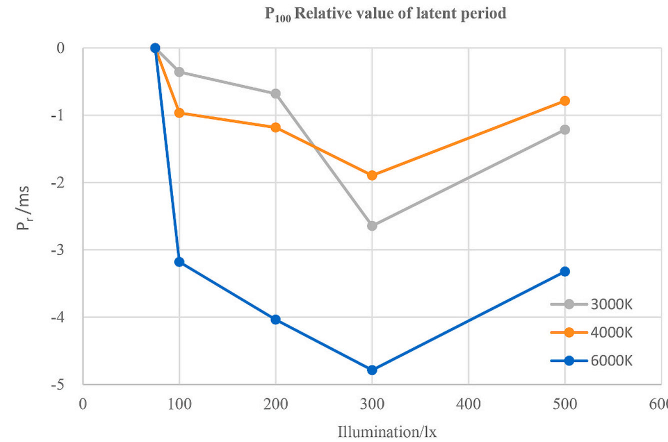

Fig. 12. The relationship between P_r and illumination and CCT.

working efficiency of the subject was not noticeable at this moment. At 6000 K, T_r increased significantly as the illuminance increased, indicating that the reading efficiency was higher than the average. Therefore, the indoor areas that need to use a cool colour temperature, efforts should be made to improve the illumination to ensure the working efficiency of the staff. Under the 4000 K light, increasing the illumination could significantly improve the work efficiency of the staff, and under the illumination of 300 lx, T_r reached the maximum, which can be considered that such light environment can significantly improve the work efficiency.

3.3. *Physiological evaluation*

3.3.1. *Visual evoked potential*

The results of one-way analysis of variance for P_r are shown in Table 14, which indicates that only illumination was a significant factor affecting P_r. Fig. 12 shows the relationship between P_r and illumination and colour temperature, indicating that the P_r at the three colour temperature levels is always less than 0, and the inflection points all appear at 300 lx. However, at the colour temperature of 6000 K, P_r is distinctly less than for the other two colour temperatures, indicating that with the increase in illumination, the visual acuity of all the staff improved, but the amplitude tends to increase first and then decrease. Under the combination of the 6000 K colour temperature and 300 lx illumination, the human optic nerve is the most sensitive.

3.3.2. *Visual fatigue*

The results of one-way analysis of variance for the critical values of the flash fusion frequency are shown in Table 15. Illumination, colour temperature, illumination-colour temperature are all insignificant factors. These results indicate that the primary factor affecting the degree of visual fatigue reflected by the critical value of flash fusion frequency is a random error, showing poor dependence on the illumination and colour temperature.

3.4. *Comprehensive light comfort zone*

In order to obtain a comprehensive light comfort zone, two aspects of the light comfort illumination intervals of the three colour temperature levels were analysed: the relative value of the P_{100} latency period, a visually evoked EEG parameter, and subjective evaluation total score. The illumination interval greater than or equal to the optimal value of 85% was defined as the comfort zone. The comfort zone illumination interval corresponding to the two indices is shown in Table 16.

At the intersection [335.9, 409.4] of the six illumination intervals in the above Table 16, (unit: lx), within this illumination range, the optic nerve and subjective comfort under the light of the three colour temperatures of 6000 K, 4000 K, and 3000 K are within the comfort range. The comprehensive light comfort zone is shown in Fig. 13.

Table 14
The results of One-way ANOVA (P_r).

	Type III square sum	df	Mean square	F	Sig.
Illumination	113.005	2	56.506	4.316	0.016
CCT	102.325	4	25.581	1.954	0.108
Illumination × CCT	36.811	8	4.601	0.351	0.943

Table 15
The results of One-way ANOVA (flash fusion frequency).

	Type III square sum	df	Mean square	F	Sig.
Illumination	22.148	2	11.074	1.311	0.271
CCT	14.975	4	3.744	0.433	0.777
Illumination × CCT	9.124	8	1.141	0.135	0.998

Table 16
Corresponding illumination range for light comfort zones.

Evaluation index	CCT/K	Illumination/lx
P_{100}	6000	[217.5, 438.4]
	4000	[213.3, 409.4]
	3000	[242.6, 443.4]
Subjective evaluation	6000	[253.9, 498.2]
	4000	[335.9, 691.5]
	3000	[303.8, 611.6]

4. Discussion

4.1. *Significance analysis*

Fig. 14 is the summary of the significance of illumination and colour temperature for the subjective evaluation, task evaluation, and physiological evaluation. The results demonstrate that illumination or illumination–colour temperature is always a significant factor affecting the quality of the office light environment. From the perspective of the subjective evaluation, the comprehensive score, i.e. satisfaction, which was established in this experiment to be within the range of 75–500 lx, has shown a trend of “diminishing returns”. Comparing domestic and foreign studies, the illumination under which the optimal value of each index appears is not the same due to the different indicators set in the subjective evaluation and the limitations of the research scope.

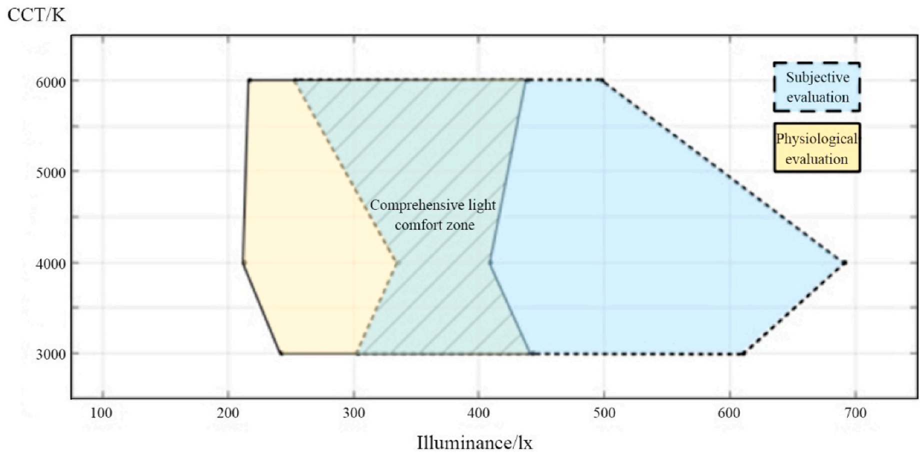

Fig. 13. Comprehensive light comfort zone.

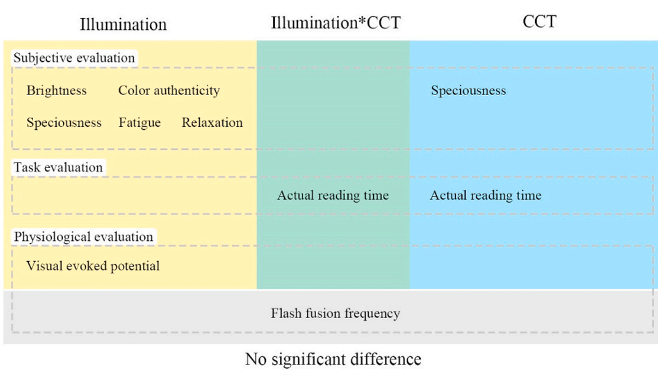

Fig. 14. Significance of illumination and correlated colour temperature (CCT). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Therefore, there are two trends in the evaluation: one shows a monotonically increasing or decreasing trend, while the other shows a parabolic trend. When the scores of all the indices were integrated, the interval of the optimal value of illumination in a particular scenario can be determined roughly. In the different scenarios, it is only necessary to change the emphasis of the subjective indicators. However, as for the optimal colour temperature, the working conditions are not only related to the nature of work, but also to the fatigue of the people exposed to the environment for a long time. Therefore, the optimal combination of illumination and colour temperature should be selected according to the actual situation.

Based on the physiological evaluation, the arousal level of the human body, as well as the visual acuity, was improved with the increase in the illumination, which is beneficial within the scope of this study. However, Lan's research found that 3000 lx illumination exceeded the optimal arousal level, which was not conducive to improving the performance for complex or difficult tasks. In addition, too much illumination produces excessive biological energy in the eyes, which becomes a burden on the optic nerve and causes visual fatigue prematurely [15].

Unfortunately, this paper only discusses the effect of illumination and colour temperature on objective visual fatigue in the case of short-term exposure. As a result, its actual effect is concealed by the random error of the critical value of the flash fusion frequency. The author still believes that the combined effect of illumination and colour temperature on visual fatigue may be manifested during long-term exposure.

In Figs. 11 and 12, the trend lines of the 3000 K and 4000 K colour temperatures cross once, and we cannot give a specific explanation. Therefore, we will further study the cause of this phenomenon.

4.2. *Limitations of this research and further study*

In order to minimize the interference of irrelevant factors in each experiment, closed chambers containing only artificial lighting were selected as the experimental environment. In actual situations, however, most of the indoor office lighting environment is jointly created by natural and artificial light, including direct sunshine and only scattered light. Therefore, there is a variation between the experimental environment and the actual conditions.

In this experiment, only the colour temperature and average illumination of the working face were considered. In reality, the indoor light environment is affected by multiple factors such as lighting mode, glare, and brightness ratio. I. T. Kim et al. considered the influence of spectral power, luminous flux, and interior decoration on human physiology and psychology [40]. All these factors should be considered when evaluating an indoor light environment.

In the visual evoked potential test, the controlled display screen was always at the maximum brightness, and the effect of the ambient illumination and screen brightness contrast was not considered [41,42]. It is insufficient to analyse the data only in the time domain, so a method of wavelet transform and energy analysis can be used to explore the time-frequency energy distribution, or a method of empirical mode decomposition and extraction of characteristic values [43] could be adopted to classify visual evoked potentials under varied conditions.

Therefore, if a controllable natural light source can be added to make the experimental conditions closer to the real scenario, and the physiological parameters can be further explored, more realistic comprehensive evaluation results can be obtained for the direction and guidance of the design and optimization of indoor light environments to improve the comfort levels.

5. Conclusion

Through changing the combination of the illumination and colour temperature of a light source, this study determined the effects of different light environments on people from three aspects: subjective evaluation, task evaluation, and physiological evaluation. Improving the illumination can always helps improve the subjective comfort of people, but the effect decreases gradually. Controlling the average illumination of the working face at 300 lx is sufficient to make people feel comfortable. Increasing illumination of the working surface helps improve the working efficiency of the staff, especially under the light source with a colour temperature of 4000 K, where the working efficiency of the staff can be significantly improved by improving illumination. Therefore, the lighting of 4000 K can be used in such venues as a library, where long-term reading and processing of paper materials are common. The physiological evaluation show that the response speed of the visual centre is related to illumination and is the fastest under the combination of 6000 K and 300 lx, but the correlation between the critical value of the flash fusion frequency and illumination and colour temperature is poor. Further study is needed for an objective evaluation of the relationship between visual fatigue and illumination and colour temperature using this method. Based on the comprehensive analysis of these conclusions, the light comfort zone illumination (lx) interval corresponding to high, medium, and low colour temperatures is [335.9, 409.4], which could be a valuable reference for the design and optimization of the office lighting environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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