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Effects of indoor lighting environments on paper reading efficiency and brain fatigue: an experimental study

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Introduction: This study investigated the influence of indoor lighting environments on paper reading efficiency and brain fatigue to explore lighting parameters that benefit users during various reading durations.

Methods: The study was conducted in the Smart Lighting Lab, where 12 participants were tested under different illuminance levels and correlated color temperatures (CCT) for three distinct reading durations. Reading efficiency during the task tests and objective measures of brain activity by monitoring participants' electroencephalograms (EEGs) were used as key factors to assess participants' fatigue levels.

Results: By analyzing the subjective and objective results, we found that paper reading efficiency was significantly affected by changes in the lighting environment. Also, based on the results of this study, we propose lighting recommendations for paper reading tasks of different durations. For a 15 min reading task, the lighting condition of 500 lux-6,500 K were the most efficient for reading; for a 30 min reading task, 500 lux-4,000 K lighting environments were found to be the most effective; and 750 lux-6,500 K was the best lighting environment for a 60 min reading duration.

Discussion: These suggestions can serve as a reference for designing indoor lighting environment. In addition, they provide guidance to researchers and reviewers conducting similar studies.

KEYWORDS

indoor lighting environment, reading efficiency, brain fatigue, EEG, reading durations

1 Introduction

In recent years, increased indoor lifestyle have emphasized the significant impact of indoor lighting on health and work efficiency (Peeters et al., 2021; Collier et al., 2023). This trend highlights the urgent need for modern technology and human-centered approaches (Menendez-Velazquez et al., 2023), especially in terms of improving aspects like light color, intensity, and color temperature (Kaymaz and Manav, 2023). In this context, the indoor reading environment becomes particularly important. A well-designed lighting environment not only provides convenience and comfort but also helps protect visual health, enhance task efficiency and reduce discomfort (Liu et al., 2020).

The lighting environment is influenced by various parameters, including color rendering, glare, illuminance levels, illuminance uniformity, and color temperature

(Chuanbo.magtechjournal, 2023). Within the field of indoor lighting, we typically focus on two primary characteristic parameters: Correlated Color Temperature (CCT) and illuminance. These parameters play an important role in indoor lighting environments (Hu et al., 2022; Choi et al., 2022). However, different countries and regions have varying standards for classroom illuminance. China's "Architectural Lighting Design Standards" GB 50034-2013, specify a minimum of 300 lux for classroom illumination (Hu et al., 2021). The American Institute of Lighting Engineering recommends at least 500 lux for classrooms and labs where studying is frequent. The Japanese Industrial Standard suggests a range of 500–750 lux for classroom illumination. CIE's "Lighting of Classroom" guidelines state that reading and writing tasks require an average illumination of at least than 500 lux (Davis, 2017; Mills and Borg, 1999). Additionally, changes in color temperature can impact emotions, attention, and comfort (Llinares et al., 2021). Low color temperature(2700 K)promotes positive emotions, creating a warm and relaxed lighting atmosphere (Yu and Akita, 2019). During this time, people also respond more rapidly to emotional images (Li et al., 2021). Neutral color temperature(4000 K) is considered more suitable for task-oriented activities such as reading and dining, as well as for classroom lighting environments (Dugar and Agarwal, 2019; Yang and Jeon, 2020). Higher color temperatures help to enhance performance in attention and memory tasks, making them suitable for activities that require a high degree of concentration (Maier et al., 2017).

Different indoor environments, especially workplaces, directly impact work efficiency and indirectly affect people's attention and motivation (Morrice et al., 2021). For various scenarios and tasks, such as office lighting, a color temperature combination of 750 lux and 4000 K has been found to help reduce visual fatigue. Conversely, combinations of low illuminance and low color temperature, or high illuminance and high color temperature, may lead to more severe visual fatigue (Chen et al., 2023). Therefore, choosing appropriate lighting conditions is crucial for improving learning and work efficiency. Different lighting conditions also have a linear relationship with attention level (Fu et al., 2023a). Under conditions of 300 lux and 6000K, it is more suitable for highly concentrated attention for thinking and analyzing (Lan et al., 2021). In lighting conditions of 500 lux and 5000K, attention and work efficiency are at their highest with fatigue at its lowest (Yu and Akita, 2023). Under 1,000 lux and 5000 K conditions, individuals display optimal working memory performance but perform less effectively under conditions of 400 lux and 7000 K (Lee and Kim, 2020).

Objective experimental methods and physiological indicator measurements can quantify fatigue (Fang et al., 2022). Experiments involving work performance and differential attention tests have shown that both illuminance and color temperature are related to comfort and relaxation (Chen et al., 2022a). In experiments using pointer meter reading materials, neutral color temperature is generally used to enhance reading efficiency (Lu et al., 2020). By monitoring physiological parameters in electroencephalograms (EEG), physiological indicators can provide real-time indications of fatigue and evaluate cognitive workload during human cognitive tasks (Guan et al., 2022; Mehmood et al., 2023). Asymmetrical activity in the brain's frontal lobe has been shown to be highly correlated with subjective questionnaires and objective task performance, making it a more objective indicator to validate traditional subjective questionnaire-based methods (Niu et al., 2022; Mir et al., 2022). Frequent waves in EEG, such as the low-frequency θ and α waves and high-frequency β waves, can be utilized to assess fatigue (Wang et al., 2023). α and β parameters have been found to be effective for measuring fatigue (Chai et al., 2022), with α wave oscillations reflecting fundamental cognitive processes and playing a critical role in integrating brain activities across different frequency ranges (Ippolito et al., 2022). Different wavelengths have also been shown to impact neurophysiological and neuropsychological parameters (Mankowska et al., 2022). Several studies have also explored the relationship between physiological changes and lighting environment. Under higher illumination, reduced pre-stimulus α activity is associated with delayed reaction times in sustained attention tasks (Chen et al., 2022b; Sun et al., 2022). Based on EEG signals of sustained attention tasks, it has been found that subjects experience better visual comfort at CCTs of 3300 and 4300 K and illuminance levels of 300 lux (Fu et al., 2023b). Monitoring EEG under different ambient light tests has revealed that improving illumination and color temperature in the workplace contributes to reduce fatigue (ZHU et al., 2015).

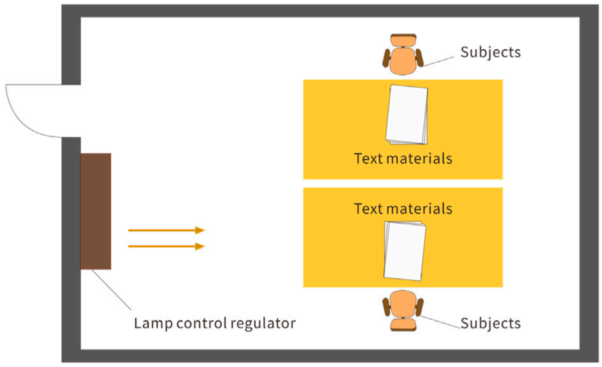

FIGURE 1
Detailed layout of the space.

However, based on the literature review, few studies have comprehensively considered the impact of lighting environments on physiology and reading efficiency from the perspective of different reading durations. Therefore, this paper aims to investigate the effects of reading duration, color temperature, and illuminance on human physiology and work efficiency, and to provide personalized recommendations for indoor lighting solutions for different reading durations. The experiment was conducted in a lighting laboratory without daylight. Users' results were collected for assessing physiological changes and work efficiency under different lighting conditions. Finally, we propose suggestions for indoor lighting schemes applicable to different reading durations based on the experimental results. The originality of this study is reflected in two aspects:

1. In contrast to previous studies that focused on single factors or specific task conditions, our research considers the impact of multiple factors of color temperature and illuminance on human physiology and work efficiency under different reading durations.
2. Personalized indoor lighting scheme recommendations are provided based on three different reading durations to enhance learning and work efficiency and reduce fatigue.

TABLE 1 Configuration of lamps and lanterns.

Equipment	Brand	Illuminance	Color temperature	Quantity
LED Tube	Philips T5	0–1000lx	2700 k	3
LED Tube	Philips T5	0–1000lx	4000 k	3
LED Tube	Philips T5	0–1000lx	6500 k	3

TABLE 2 Classroom lighting specifications.

Venue/Illuminance	Classroom	Laboratory (lx)	Art room (lx)	Multimedia room	Classroom blackboard
	300lx–500lx	500	750	150lx–300lx	300lx–500lx

2 Materials and methods

2.1 Experimental setup

2.1.1 Space

The experiment was conducted in a full-scale mock-up classroom, with dimensions of 300 cm in length, 200 cm in width, and 400 cm in height. Two desks with dimensions of 1.2 m (L) × 0.6 m (W) × 0.75 m (H) were placed in the space. Figure 1 shows the detailed layout of the space.

To prevent the influence of external light on the experiment, professional blackout curtains were installed on the inner side of the windows to minimize reflections. Additionally, to avoid the potential for glare from the light source, this experiment required that the vertical distance between the light fixture and the tabletop, as well as the horizontal distance between the participants and the paper-based reading materials, be no less than 60 cm.

The lighting equipment included Philips T5 LED lamps. Nine LED lamp tubes were placed on a shelf at an appropriate distance. Adjustable lighting devices were mounted on the wall, allowing illumination to be adjusted within a range from 0 to 1,000 lux. The configuration detailed list of lamps and lanterns are provided in Table 1.

2.1.2 Lighting conditions

Illuminance, measured in lux (lx), refers to the amount of visible light energy received per unit area. While higher illuminance levels can improve our ability to perceive light, excessive levels can have the opposite effect. Color temperature is the usual way to indicate the spectral quality of a light source. Light sources with a low color temperature have a higher proportion of red radiation in their energy distribution, known as "warm light". As the color temperature increases, the proportion of blue radiation also increases, known as "cool light" (Masullo et al., 2022). Changes in color temperature can affect how people feel, such as comfort, pleasure, seriousness, or coldness. The architectural lighting design standard GB 50034-2013, it stipulates the standard color temperature values of 2,700 K, 4,000 K, and 6,500 K for different indoor lighting applications. Additionally, the standard also indicates that the illumination in the indoor environment should typically fall within the range of 300–750 lux. The various types of classroom lighting environment specifications are given in Table 2.

To eliminate the impact of variations in human thermal comfort during the experiment, the laboratory environment was controlled at a temperature range of 23°C–25°C (Celsius) and a relative humidity between 30% and 70%, ensuring that the participants were within a comfortable range (Masullo et al., 2022).

FIGURE 2
EEG equipment.

Based on the requirements of the above specifications for the lighting environment and comfort, in this experiment, the illuminance parameters were set at 300 lux, 500 lux, and 750 lux, while the color temperature parameters were 2,700 K, 4,000 K, and 6500 K. The temperature was maintained between 23 and 25°C, and the humidity was in the range of 30%-70%.

2.1.3 Equipment

In this experiment, a 16-channel EEG device and 16-channel electrode caps manufactured by Beijing Mind Ark were used for EEG data acquisition. A Dell desktop computer was also installed to connect to the EEG equipment for real-time EEG monitoring. Figure 2 shows the experimental EEG equipment. Illuminance and color temperature were measured with the Konica Minolta CL-200A Color Illuminance Meter. Timing was performed with a timer.

2.2 Subjects

A rigorous selection process was implemented to ensure that participants met specific criteria, including good overall health,

TABLE 3 Participant information.

Participant	Gender	Age	Vision
P 1	Female	20	Myopia
P 2	Male	22	No Myopia
P 3	Male	19	No Myopia
P 4	Female	18	Myopia
P 5	Male	21	Myopia
P 6	Female	19	Myopia
P 7	Male	22	Myopia
P 8	Male	23	Myopia
P 9	Male	20	Myopia
P 10	Male	19	Myopia
P 11	Female	21	Myopia
P 12	Female	22	No Myopia

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1	55461 55461	93479 93479	22361 22321	60708 60708
2	64178 64178	65596 65596	76820 76820	42196 42196
3	52284 52284	38852 38852	98086 98086	84515 84515
4	74416 74716	89518 89518	55376 55376	33294 33294
5	90707 90707	87852 87852	28977 28977	52818 52818

FIGURE 3
The test material.

sufficient cognitive abilities, and normal vision. Given the prevalence of college student in today society and the feasibility of this experimental manipulation, the subjects consisted of 12 selected graduate students, with an equal representation of both genders and ages ranging from 18 to 23. All participants were physically and mentally fit, with excellent visual acuity of at least 5.0 on the standard logarithmic visual acuity chart, even after receiving any necessary optical correction. The experiment required the subjects to maintain their normal working and resting routines in the 8 h preceding the experiment to ensure they had received adequate sleep. Additionally, no physical or mental exercise was performed within 2 h before the experiment to prevent any potential effects on their energy or excitement levels. Subject information is provided in Table 3.

2.3 Experimental materials

The experimental materials consisted of a number correction test, printed on A4-sized paper with a 12-point Times New Roman font. Subjects were to find different sets of numbers from two sets of contrasting numbers within a specified time, using "√" (for correct) and "×" (for incorrect) to mark them. This is shown in Figure 2. To counterbalance any potential sequence effects, an AB-BA design was employed for the presentation order of the number correction materials. This test simulated reading tasks in daily life that require rapid and accurate processing of information. The test material for "Number Correction" shown in Figure 3.

2.4 Experimental process

In complex multi-factor and multi-level studies, orthogonal experimental design methods are typically used to select representative experimental combinations for testing (Sun et al., 2020). In this experiment, three factors were involved: illuminance, color temperature, and reading duration, with each factor having three parameter levels. Therefore, we employed an L9 (3^3) orthogonal experimental design to develop the experimental plan. Table 4 demonstrated the experiment schedule.

1. The experimenters and participants first carried out relevant preparatory work before the experiment. The preparation process included an explanation of the experi-ment process and the wearing of EEG equipment.
2. Participants performed the task test for a prescribed reading duration.
3. After a 10-min intermission, the subjects entered different working conditions for the next round of the experiment.

The experimental sessions were carefully scheduled in the morning from 9:00 a.m. to 12:00 p.m. and in the afternoon from 2:00 p.m. to 5: 00 p.m. To ensure that the subjects were not disturbed, strict measures were taken to maintain absolute silence and control noise throughout the entire process. The illuminance and color temperature were precisely adjusted to follow the experimental schedule, creating a peaceful lighting environment. The participants wore EEG caps while conducting the reading tests as shown in Figure 5.

2.5 Data acquisition method

2.5.1 Reading efficiency measurement methods

The evaluation of one's reading efficiency is intertwined with two fundamental factors: reading speed and accuracy (Grbovic et al.), (Wallace et al., 2022). These elements play a vital role in gauging an individual's reading efficiency. Reading speed primarily entails how quickly one can comprehend written material, usually quantified by the number of words read per minute. Accuracy, on the other hand, measures the number of correct answers or task completion percentage. Eq. 1 defines the formula for calculating reading speed and Eq. 2 defines the formula for reading accuracy. Reading efficiency depends on both reading speed and accuracy rate. The equivalent reading efficiency was determined using Eq. 3.

$$v = r/t \quad (1)$$

$$P = n/N \quad (2)$$

$$\eta = v^{*} p \quad (3)$$

Note 1 : v = reading speed, r = the number of words read, and t = the reading time.

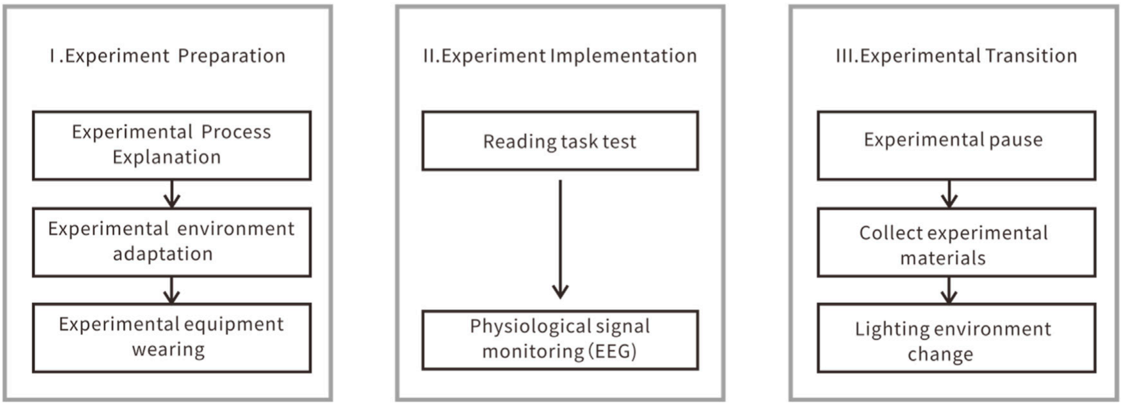

FIGURE 4
Experimental flowchart.

TABLE 4 The experiment schedule.

Experiment	Variable		
	Illuminance(lx)	Color temperature(k)	Time-duration (min)
1	300	3000	15
2	500	6500	15
3	750	4000	15
4	300	6500	30
5	500	4000	30
6	750	3000	30
7	300	4000	60
8	500	3000	60
9	750	6500	60

The experimental process was divided into three parts: Experimental Preparation, Experimental Implementation, and Experimental Transition. The experimental process is depicted in Figure 4.

FIGURE 5
The participants in the experiment.

TABLE 5 Relevant brain regions and the corresponding physiological states.

Type	Frequency	Location	Physiological state
δ	0.5–3.5	The anterior frontal region	Deep sleep, unconscious
θ	3.5–7.5	The temporal lobe	Consciousness interrupted; body relaxed
α	7.5–12.5	The highest is occipital region, followed by the parietal and frontal regions, the lowest is temporal region	Clear consciousness, relaxed body
β	12.5–30	Scattered throughout the entire scalp, primarily in the central and frontal areas	Body gradually tensing, feeling mentally and physically exhausted

Note 2 : P = reading accuracy, n = accuracy in answering questions, and N= Number of questions answered correctly.

Note3 : η = reading efficiency, v = reading speed, and p = accuracy.

For this experiment, we adopted the original reading material design. By analyzing the correct rate and reading speed of the subjects, their reading efficiency can be judged, reflecting the degree of fatigue in paper reading under various lighting environments.

2.5.2 Physiological methodology

In cognitive research, individuals require coordinated activity in multiple brain regions, including the frontal lobe, parietal lobe, cerebellum, and occipital lobe when dealing with tasks ranging from simple to complex (Fogassi and Luppino, 2005). In our everyday thinking and cognitive activities, the frontal and parietal lobes are typically the most active brain regions (Sammer et al., 2007). Electroencephalography (EEG) is an important tool used to assess brain function by visualizing fluctuating brain activity on a two-dimensional plane (Foged et al., 2022; Lassagne et al., 2022). It records the spontaneous electrical activity of pyramidal dendrites in the brain cortex, effectively reflecting the degree of brain fatigue and cortical excitability (Lin et al., 2015). Different colors represent different levels of brain activity and can be analyzed by color changes (Mostafavi et al., 2023). Therefore, in this study, we chose to use EEG signals to evaluate the impact of different lighting environment parameters on fatigue by comparing the activity levels in the frontal lobe (F3, F4, FZ) and central area (C3, C4, CZ). Table 5 presents the relevant brain regions and their corresponding physiological states.

3 Results

3.1 Reading efficiency

The reading efficiency tests were conducted in a controlled paper-based reading environment to ensure experimental consistency. Several studies have demonstrated a strong relationship between paper-based reading tasks and lighting conditions (Shamsul et al., 2013). This study comprehensively considered different reading durations to explore the impact of lighting conditions on reading efficiency. Data collection and analysis were carried out using Microsoft Excel and SPSS 27.0 software to ensure data accuracy and reliability. The experimental data were normally distributed with a significance level of 0.05. ANOVA was used to examine the effects of different factors on reading efficiency. The results showed that illuminance and color temperature had a significant effect on reading efficiency, with F = 3.062, p = 0.012 < 0.05 and F = 4.298, p = 0.02 < 0.05, respectively.

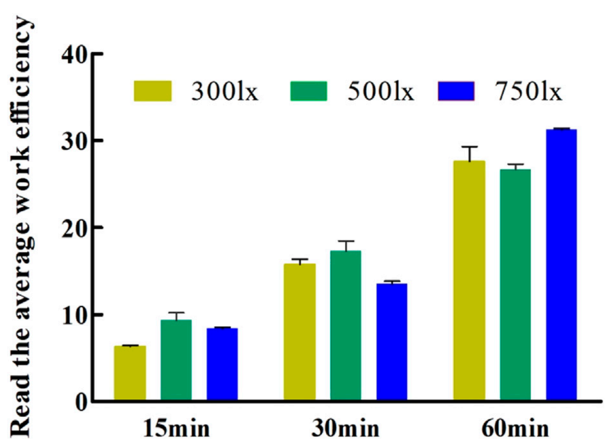

FIGURE 6
The average reading efficiency under the illuminance.

The results show that for 15-min and 30-min reading durations, 500 lux illumination yielded the best reading efficiency. However, as the reading duration to 60 min, an illuminance of 750 lux became the preferred choice. Figure 6 illustrates the average reading efficiency under the intensity of illuminance levels for different reading durations.

The results showed that the color temperature of 6,500 K had a positive effect on obtaining the highest reading efficiency at 15 min of reading duration. But at the 30 min paper reading duration, a color temperature of 4,000 K showed higher efficiency. It is worth noting that as the reading duration increased to 60 min, the optimal CCT again returned to 6,500 K to achieve the highest reading efficiency. Figure 7 displays the average reading efficiency under the intensity of correlated color temperature (CCT) for different reading durations.

Overall, the research results clearly show that both illuminance and CCT are two critical factors influencing reading efficiency, and their specific effects vary by reading duration. The findings of this study indicate that for a 15 min reading duration, the optimal lighting conditions were 500 lux and a CCT of 6,500 K. At a 30 min of reading duration, 500 lux and 4,000 K color

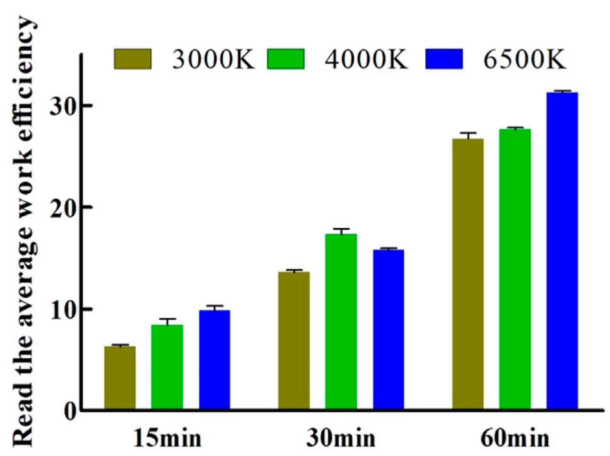

FIGURE 7
The average reading efficiency under the color temperature.

temperature achieved the highest reading efficiency. Lastly, for a 60-min reading duration, a combination of 750 lux illuminance and a CCT of 6,500 K provided the highest efficiency for paper-based reading.

3.2 EEG

The electroencephalogram (EEG) offers high time resolution and excellent characteristics in the frequency domain (Van Der Cruijsen et al., 2021). Electroencephalography topographical representation can reflect changes in brain function and express color intensity changes, using this, a percentage topographic map of the ratio between different brain wave frequency band combinations can be obtained. In this experiment, the EEG topographical of the subjects at the beginning was compared with that near the end of the task. The change in the state at the end of the task had a significant effect on the energy distribution of different rhythm waves in the EEG. We further analyzed the EEG topographical to measure the degree of fatigue.

In experiments conducted with 15 min reading durations, we tested various lighting environments, including 300 lux–3000 K, 500 lux–6,500 K, and 750 lux–4,000 K. The results showed significant activation in the central and frontal regions of the brain, along with the presence of positive components in these areas. As shown in Figure 8, the change in state after the task test had a significant effect on the energy distribution of the different waves in the EEG. This finding helped determine that the lighting environment with an illuminance of 500 lux and a color temperature of 6500 K was the most suitable for tasks with this duration of reading.

After 30 min of reading in three different lighting environments, the highest level of brain activity was observed in the parietal and central regions, with some activity in the frontal regions as well. The red areas on the brain scans represented high activity levels, while darker red shadows reflected higher degree of fatigue. The results showed that the central region exhibited relatively low brain activity levels and lighter red areas near the end of the 30 min reading task. Specifically, the 500 lux-4,000 K lighting environments exhibited the lowest degree of brain fatigue, making it the optimal choice for the 30 min reading duration. Figure 9 displays the EEG topographical representation for 30 min.

During a 60 min duration of paper-based reading, specific lighting parameters were used: 300 lux–4000 K, 500 lux–3000 K, and 750 lux–6500 K. When the lighting was set to 750 lux and 6500 K, near the end of the experiment, participants' central and frontal brain regions exhibited shallower red shadows, indicating lower activity levels. The results suggest that this lighting environment helped reduce fatigue and supported extended periods of reading tasks (Figure 10).

4 Discussion

4.1 Comprehensive analysis of light environment, efficiency and physiological

Based on the results of the previous section, it can be concluded that the lighting conditions in this study have an impact on both reading efficiency and physiological states. During this experiment, we measured the physiological state of the subjects' EEG topographical and observed that the physiological effects of lighting conditions varied significantly with different reading durations. This suggests that the optimal lighting environment in the experiment varies with different reading durations. The results also indicated that with the increase of reading duration, the illuminance gradually increases, but the color temperature did not increase correspondingly. In conclusion, the experimental results clearly indicated that illuminance and color temperature had a significant impact on reading efficiency, and changes in lighting conditions also affected fatigue levels.

4.2 Suggestions for lighting environments for different reading durations

Several recommendations were proposed for different reading durations. For reading durations of 15 or 30 min, a consistent illuminance of 500 lux is recommended. This aligns with earlier research that illuminance variations do not significantly impact productivity over short durations (Fu et al., 2023a; Yu and Akita, 2023). However, for 60-min reading duration, a moderate increase in illuminance is suggested to achieve optimal lighting conditions (Bao et al., 2021). This finding is consistent with previous studies, including that of Bania, which found that 750 lux to be more suitable than 500 lux (Baniya et al., 2015).

Additionally, the color temperature of the lighting environment showed significant changes with varying reading durations, consistent with the results of the (Janosik and Marczak, 2016) study, highlighting the importance of CCT of the light source in object recognition (Janosik and Marczak, 2016). Specifically, for a 15-min reading duration, the highest reading efficiency was observed at a color temperature of 6,500 K, while for 30 min of reading, 4,000 K was more suitable. This indicates that different reading durations have distinct effects on individuals' perceptual experiences and highlights the suitability of a 4,000 K color temperature for classroom lighting environments (Yu and Akita,

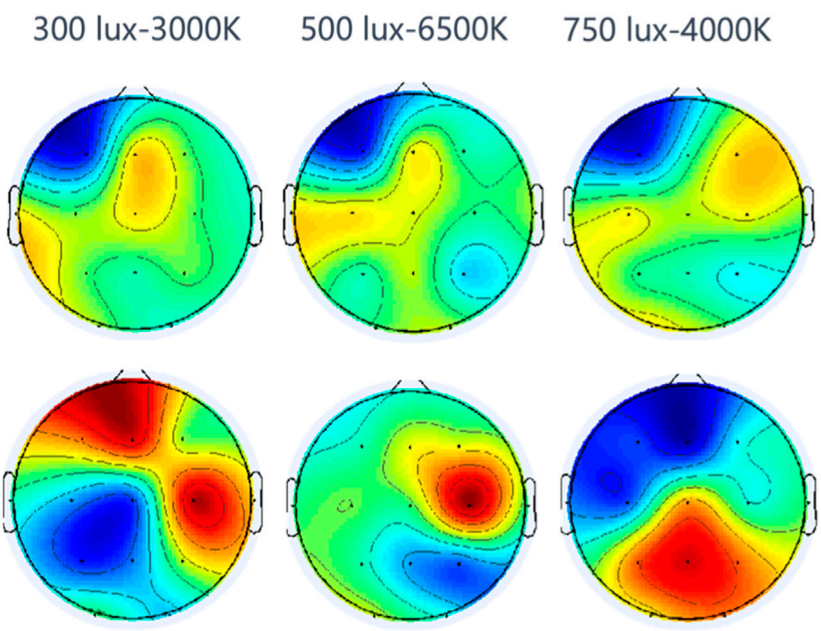

FIGURE 8
EEG topographical representation for 15 min.

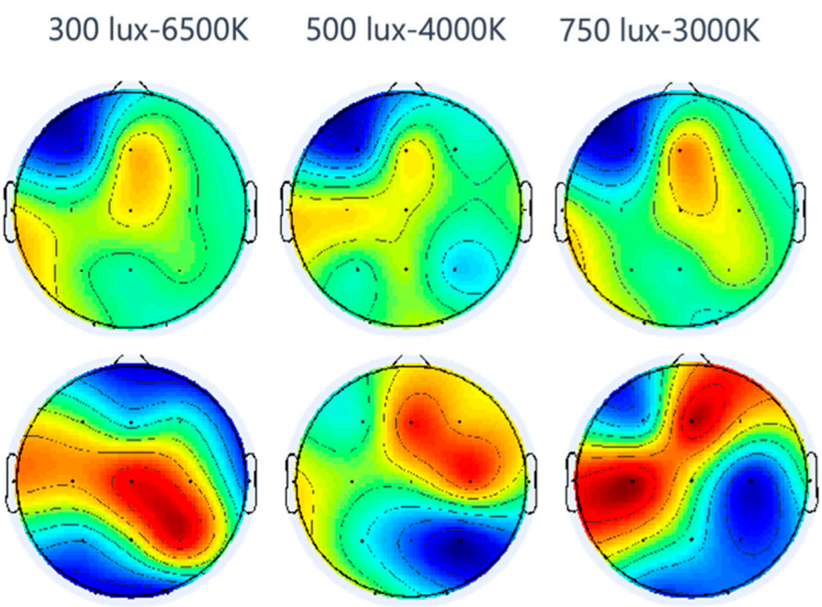

FIGURE 9
EEG topographical representation for 30 min.

2023; Shahidi et al., 2021). For 60-min reading durations, the color temperature returned to 6,500 K. Other factors may have contributed to this result, such as those resulting from the long duration of this experiment or the small sample size of subjects.

Given that practical applications often involve considering various factors, combined with the results of the previous experiments, we provide lighting suggestions for interior spaces with different reading durations. By carefully selecting the appropriate combination of illuminance and color temperature, the overall reading experience can be enhanced, fatigue can be reduced, and efficiency can be improved. These suggestions can be used in reading areas such as libraries, classrooms, study rooms, and even aerospace industry cockpits to improve the design and optimization of lighting environments.

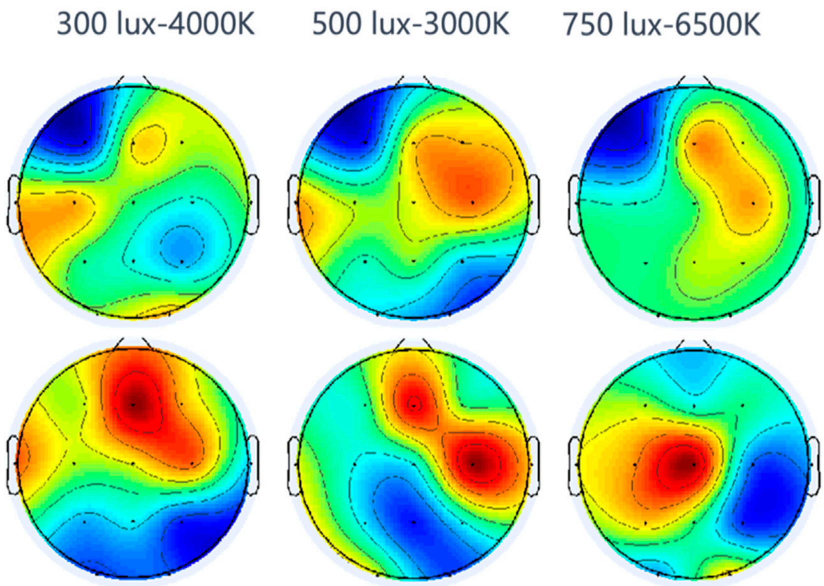

FIGURE 10
EEG topographical representation for 60 min.

5 Conclusion

In this study, we investigated the combined effects of illuminance and Correlated Color Temperature (CCT) parameters in daily LED lighting. Subjects engaged in paper reading task under three different durations. We collected real-time electroencephalography (EEG) physiological data from participants and, in conjunction with reading test results, conducted an objective analysis to quantify the level of fatigue during paper reading. The study found that improving the illuminance and color temperature of the reading environment enhanced reading efficiency and reduced fatigue at different reading durations. The results showed that an indoor illuminance of 500 lux and a color temperature of 6,500 K were optimal for 15-min reading durations. For 30-min reading durations, illuminance of 500 lux and a color temperature of 4,000 K were more appropriate. For 60-min reading durations, illuminance of 750 lux and a color temperature of 6,500 K provided the best conditions. It is important to note that the results were obtained using specific measurements and tools, and future studies may benefit from the use of multiple methods and tools to comprehensively examine the relationship between CCT, illuminance, reading efficiency, and fatigue. The focus of this experiment was to explore the correlation between lighting parameters and reading efficiency, fatigue from an ergonomic perspective, with the aim of providing guidance for the design of lighting environments that optimize reading efficiency for various reading durations.

In this research, we mainly used artificial light devices to provide lighting, but daylight fluctuation may also influence fatigue. Therefore, future studies could explore lighting environments with a combination of natural and artificial light to fully explore this issue. There are some limitations to this study. Firstly, the division of reading durations in this experiment was relatively broad and may not encompass a wider range of reading scenarios, such as a 50-min classroom lesson or a 90-min examination. A more detailed categorization would provide a closer approximation to the real situation. Secondly, the impact of the subject's physical factors, such as age and degree of myopia, on the experimental results should be considered. In this study, all the participants were limited to graduate students, and the results cannot establish a potential relationship between age variability and fatigue. In future research, participants from different age groups should be included, and various reading durations scenarios could create a more realistic experimental environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Huanghuai University Academic Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

AZ: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. YP: Conceptualization, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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