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The Effects of Eye Illuminance Distribution in the Horizontal Field of View on Human Performance in a Home Paper-Based Learning Situation

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Abstract: Previous studies have focused on task/ambient illumination for visual effects and eye illumination for non-visual effects. In this context, eye illumination within the non-visual realm was defined as vertical non-visual eye illuminance. Considering the functional specificity of central vision and peripheral vision, this study aims to explore whether the distribution of eye illuminance in the horizontal field of view (FOV) affects human performance in home paper-based learning settings. In this study, a within-subject design was used to investigate the effects of eye illuminance distribution on mental perception, task performance, and physiological health while maintaining constant task illuminance and correlated color temperature (CCT). The findings revealed that eye illuminance and its distribution in the horizontal FOV had complex effects on visual fatigue, Landolt ring performance, heart rate variability, and luminous environment appraisal. A relatively optimal lighting configuration was suggested—Scene 4, which was characterized by an eye illuminance level in central FOV of 186 lx and an "m" shaped eye illuminance distribution pattern. This indicates the importance of considering eye illuminance distribution in the horizontal FOV, rather than solely focusing on vertical eye illuminance.

Keywords: distribution of eye illuminance; central vision; peripheral vision; mental perception; task performance; physiological health; home learning

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1. Introduction

It is widely accepted that improving the quality of a luminous environment has a positive impact on various aspects of human performance. Factors such as illuminance and spectrum are intricately linked to mental perception and task performance, impacting aspects like comfort [1–3], alertness [4–7], emotion [4,5,8], and visual performance [2,9,10]. Additionally, they also play a crucial role in affecting physiological health, like visual health [2,11,12]. Therefore, enhancing the quality of the luminous environment is critical for promoting human well-being.

Myopia remains a severe issue among teenagers. The increase in myopia risk might be associated with increased engagement in indoor activities, frequent utilization of electronic screens, or close-range studying under inappropriate home lighting [13,14]. It is noteworthy that studying at home has become increasingly necessary [15], particularly in the post-COVID-19 era. Studies have shown that over 50% of students study later at night, and the percentage of students who suffer from myopia has dramatically grown by 5–10% after the pandemic [15–17]. Nevertheless, the current evidence regarding the relationship between home lighting and health is limited to a small number of studies in different domains of light and health [18]. These phenomena highlight the necessity of studying the luminous environment within home learning situations.

Research on task-ambient lighting presents how different lighting configurations affect visual performance and satisfaction. Studies show that task lighting could enhance arousal levels, improve performance on paper-related tasks, and increase satisfaction [19], while ambient lighting could maintain illumination on non-task surfaces and avoid extreme luminance ratios [20]. Early experiments have demonstrated the benefit of maintaining a task and ambient illuminance ratio around 1 [21]. Furthermore, guidelines like CIE S008/E-2001 [22] suggest that the maintained illuminance of the immediate surrounding areas may be lower than the task illuminance but not excessively low.

Additionally, direct/indirect lighting could influence brightness perception through walls and ceilings, thereby affecting subjective responses [23,24]. More indirect lighting could create a sense of spaciousness in the room, evoke positive emotions [23–25], and reduce ocular discomfort [26]. Notably, overhead/peripheral lighting greatly influences the impression of the luminous environment [27], and indirect/ambient lighting could reduce people's negative emotions [28]. Generally, light settings where the indirect component had a horizontal illuminance contribution of 60% or more were favored [23]. However, long-term use of indirect lighting might lead to increased job stress, which does not support the notion of indirect lighting as unconditionally superior [26].

Recently, the development of vision neuroscience research has provided a new perspective for the study of lighting effects. The large amount of neural tissue devoted to the fovea in the primary visual cortex is dominated by P channel input (responsible for spatial and chromatic information), while the peripheral retina is dominated by M channel input (responsible for target detection, visual search, and eye movement.) [29]. And the M channel determines the functional response characteristics of visual performance [29], as its electrophysiological signal is similar to the relative visual performance model (RVP) [30]. This implies that lighting in peripheral vision can potentially affect visual performance. Simultaneously, there is a proposal to shift the metric used in standards from task illuminance to ambient illuminance and from lighting the task to lighting the space [31]. These prompt an emphasis on the study of peripheral vision.

Although previous studies have explored various spatial light distributions through task-ambient lighting systems (more general lighting or more task lighting) or direct/indirect lighting systems (directed to the ceiling or directed to the task area), the contradictions in previous studies highlighted the importance of a deeper investigation into lighting distribution. Prior studies on lighting distribution have focused on spatial characteristics, overlooking the intrinsic characteristics related to the eye, such as the functional specificities of central and peripheral vision. Therefore, it is crucial to explore whether different distributions of eye illuminance in the field of view (FOV) affect human performance, with a particular focus on the implications for home paper-based learning environments.

In this study, the horizontal FOV is divided into two sections: the central FOV and the peripheral FOV, delineated by the distinctions between central vision and peripheral vision [32]. Typically, the central FOV encompasses approximately 120 degrees around the point of fixation, while the peripheral FOV extends beyond the central FOV, covering the outer edges of the FOV (Figure 1).

This study set four scenes according to the usual lighting mode of the home environment under the premise of consistent task lighting (500 lx) to investigate the effects of different eye illuminance distributions in the FOV on human performance. This will provide case support for investigating the mechanism of lighting's influence on human performance and also put forward practical suggestions for lighting design in home learning environments.

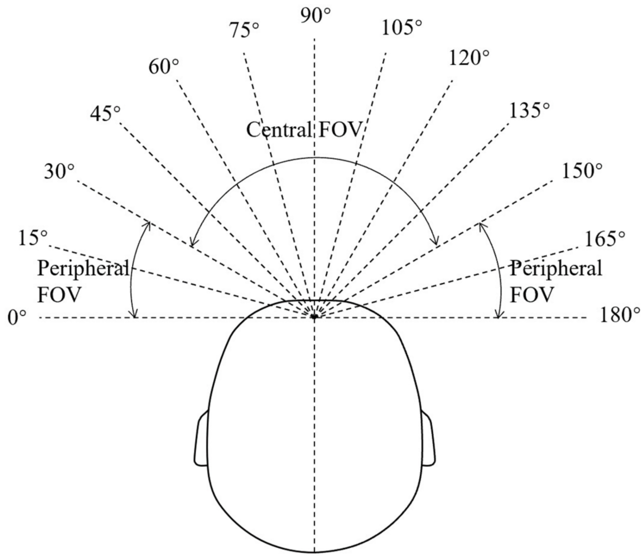


Figure 1. Divisions of the horizontal field of view (FOV) based on the central vision and peripheral vision.

2. Materials and Methods

2.1. Participants

A total of 30 Chinese college students (aged 18–26 years) participated in this study. Eligibility criteria included possessing normal or corrected to normal vision, no reported color blindness or eye deficiencies, and maintaining a regular lifestyle.

Pre-experimental preparations for participants included obtaining adequate sleep, avoiding the consumption of alcohol or caffeine-containing products, and avoiding prolonged continuous eye use. Additionally, participants should sign informed consent before the experiment.

During the analysis period, the data of those participants displaying non-serious attitudes or encountering equipment-related monitoring problems were excluded. Four participants were deemed invalid due to their error and omission rates exceeding 50% in the circled letters task (see more details in Section 2.5), and one participant was excluded for presenting over 30 errors in the visual performance test (see more details in Section 2.6.2). Additionally, four participants with atypical heart rate variability were removed from the study (see more details in Section 2.6.3). Consequently, data analysis was conducted on the remaining 21 valid participants (12 females, mean age 21.9, SD 2.04). The study was approved by the Institution Review Board of Tsinghua University.

2.2. Setup and Devices

A simulated bedroom learning environment was created in a space of roughly 3.3 × 3.3 × 2.8 m (length × width × height), with a desk (55 × 270 cm) parallel to the window (Figure 2). Artificial lighting and white full blackout curtains were used to create a stable, luminous environment to simulate nighttime learning at home. The reflectance of the main materials in this space was measured by the Minolta CM-2600d (Konica Minolta, Beijing, China) (Table 1).

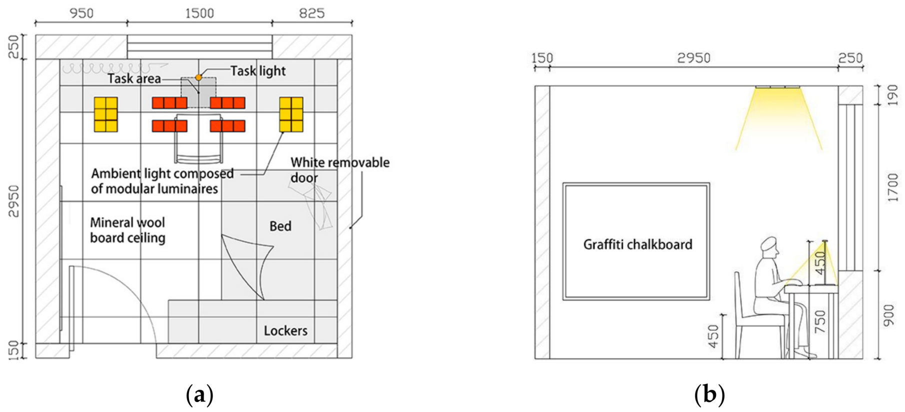


Figure 2. (**a**) The plan of the simulated bedroom learning environment; (**b**) The section of the simulated bedroom learning environment.

Table 1. Reflectance of main materials.

Material	Reflectance (SCE [1]) (%)
Desktop	10.1
White full blackout curtains	59.7
White walls and ceiling	88.2
White removable door	79.7
Wooden floor	19.2
A4 paper (with black text)	62.4

[1] SCE means specular component excluded.

The lighting system used in this study consisted of a desk lamp and ceiling lamps with continuous dimming capabilities. The light distribution curves of luminaires are shown in Figure 3. The light source of the desk lamp (15 W) was positioned 45 cm above the desk, directly in front of the participant (orange in Figure 2), and the light-emitting area of the desk lamp is shown in Figure 4. Ceiling lamps consisted of 24 modular luminaires (12 W for each luminaire), which could be divided into four groups. Two groups were positioned on the periphery (yellow in Figure 2), while the other two groups were located overhead (red in Figure 2).

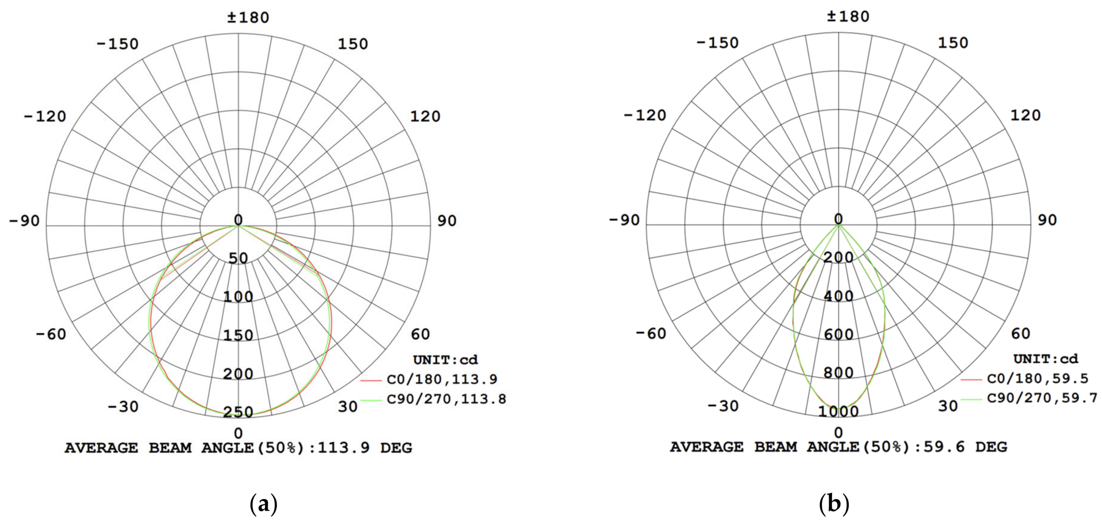
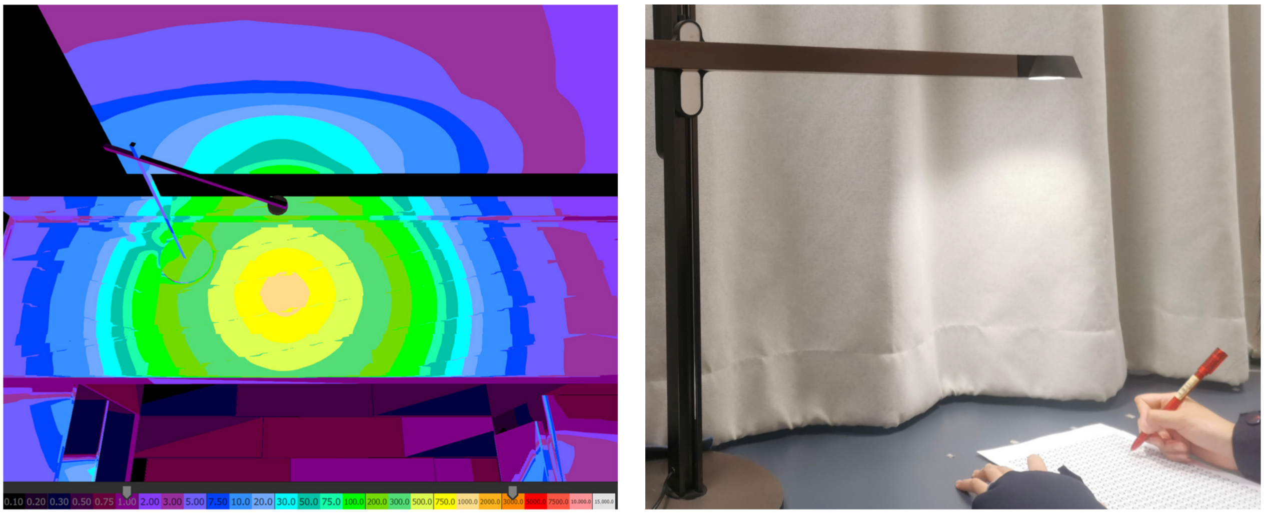


Figure 3. (**a**) The light distribution curve of ceiling luminaires; (**b**) The light distribution curve of desk luminaires.



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

Figure 4. (**a**) Pseudo-color image of the illuminance when desk lamp is 100% output; (**b**) The photograph of desk lamp source.

2.3. Experimental Design

Considering two methods for changing light distribution in the literature review, this experiment adopted a within-subject design with two levels of ceiling lamps' contribution to task illuminance (1/3 vs. 2/3) and two kinds of position (overhead versus peripheral). The horizontal illuminance recommended for home reading varies, including 150 lx in GB50034-2013 [33], 200 lx in ANSI IESNA RP-11-2017 [34], and 500 lx in JIS Z9110-2010 [35]. Given that 500 lx is sufficient to provide a pleasant environment and CCT has a negligible effect on brightness and pleasantness [36], the experiment set the task illuminance at 500 lx and CCT at 3300 K to avoid excessive blue light at night that could affect circadian rhythm.

Vertical illuminance at eye level (H = 1.2 m) was measured at 15° intervals to acquire the distributions of eye illuminance in the horizontal FOV for four experimental conditions (Figure 5). The eye illuminance distribution in Scene 1 and Scene 3 showed a "C" shape with a 90-degree rotation, while the eye illuminance distribution in Scene 2 and Scene 4 showed a similar "m" shape. The specific parameters of the four experimental lighting conditions are shown in Table 2.

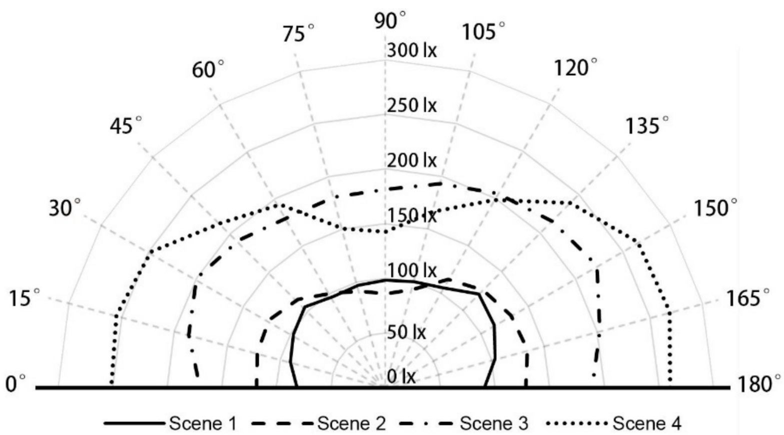
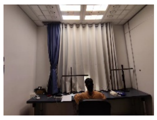
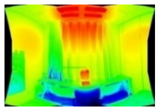
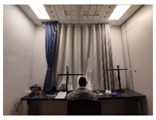
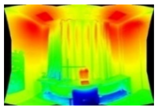
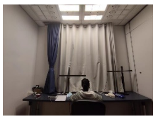
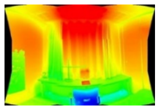
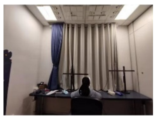
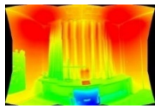


Figure 5. Four distributions of eye illuminance in the horizontal FOV. The eye measurement position is 65 cm away from the wall.

Table 2. Parameters of four experimental lighting conditions.

Scene	Independent Variables		Eye Illuminance (lx)			Task Illuminance	Equivalent Melanopic Lux [4]	Photograph	Pseudo-Color image of Luminance [5]
	Contribution to Task Illuminance	Position	E_v [1]	E_{ec} [2]	E_{ep} [3]/E_{ec}				
1	1/3	Overhead	98	103	0.94	511 lx	63.1		
2	1/3	Peripheral	86	103	1.24	514 lx	53.8		
3	2/3	Overhead	182	192	1.01	509 lx	113.4		
4	2/3	Peripheral	143	186	1.41	506 lx	87.1		

[1] Vertical eye illuminance. $E_v = E_{90^\circ}$. [2] Average eye illuminance of the central FOV. $E_{ec} = (E_{45^\circ} + E_{60^\circ} + E_{75^\circ} + E_{90^\circ} + E_{105^\circ} + E_{120^\circ} + E_{135^\circ})/7$. [3] Average eye illuminance of the peripheral FOV. $E_{ep} = (E_{15^\circ} + E_{165^\circ})/2$. [4] Equivalent Melanopic Lux (EML) is the light of a given light source experienced by the circadian system as an equivalent of photopic lux [37]. Meanwhile, it is a proposed alternate metric that is weighted to the ipRGCs. EML = M/P (melanopic to photopic) ratio × E_v (vertical illuminance). [5] The pseudo-color image of luminance is tested by the EVERFINE LGM-200B lighting glare measurement system (EVERFINE, Hangzhou, China).

2.4. Procedure

Each participant underwent four experimental conditions during the same period on 4 separate days in the laboratory with constant temperature (20–23 °C) and humidity (35–50%). Five-time slots were available each day: 18:00–18:40, 18:40–19:20, 19:20–20:00, 20:00–20:40, and 20:40–21:20. The sequences of experimental conditions, Landolt ring tests, and reading materials were in a counter-balanced order to eliminate any potential for result deviation, like the learning effect.

The experimental procedure is shown in Figure 6. The full experimental design included four sessions, one session for each of the four days. In one session, participants commenced by resting their eyes for 10 min in the waiting room. After entering the laboratory, participants were instructed to sit in front of the desk and keep their eyes 33 cm away from the task area. Participants sat for lighting adaptation while wearing a chest strap sensor to record electrocardiogram (ECG) data as baseline data. Subsequently, they undertook the visual fatigue scale and visual performance tests (pre-test). Next, the participants need to read English material for 15 min in an experimental luminous environment with continuous recording of ECG data to monitor physiological responses. After reading, the participants completed the visual fatigue scale and visual performance test again (post-test). Finally, an online questionnaire was administered.

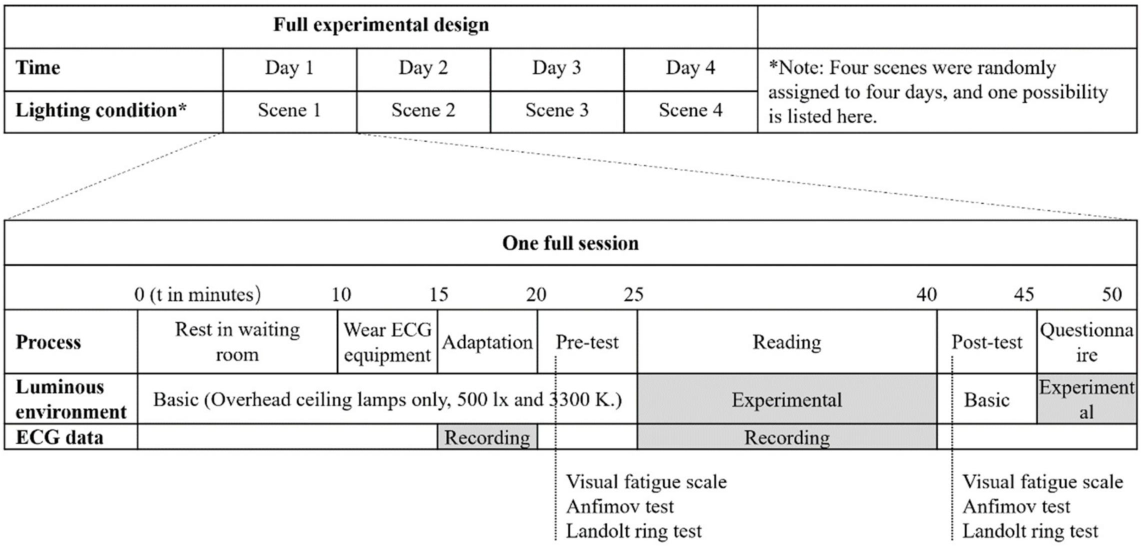


Figure 6. Schematic representation of one experimental condition.

2.5. Reading Task

This study selected reading as the study task, which is quite common in learning situations. Considering that all subjects have passed College English Test Band 4 (CET-4), four English fairy tales were selected as reading materials. English fairy tales were preferred as they allowed for circling assigned letters while reading to facilitate a precise assessment of the participants' involvement. In each experimental condition, participants read one single story printed on A4 paper using a 13-point Times New Roman font in black. After reading, participants were required to summarize the content. The degree of participants' involvement was assessed by the accuracy of circling assigned letters, which was also one of the indicators for selecting valid subjects.

To determine the duration of the reading task, a pre-experiment was conducted. 26 participants (14 females, M = 21.9 years, SD = 1.93 years) read English fairy tales for 15 min, while 28 participants (17 females, M = 21.9 years, SD = 2.08 years) read for 30 min under the same lighting conditions (500 lx and 3300 K). Each participant reported their degree of visual fatigue before and after reading. The results showed no significant difference between the 15-min reading and the 30-min reading. Moreover, prior research has shown that a duration of 20 min is enough to make a significant difference for near visual acuity [11], and 15 min can affect task performance and cortisol secretion [38]. Based on the above information, the duration of the reading task was ultimately determined to be 15 min.

2.6. Evaluation and Statistical Analysis

Considering that cognition, emotion, and alertness may affect visual performance through factors like motivation and preference [39,40], and biologically required lighting characteristics frequently do not match lighting requirements for subjective comfort or for personal activities [41], evaluations in this study will include mental perception (subjective visual fatigue, satisfaction, alertness, emotion), visual performance, and physiological health.

2.6.1. Mental Perception—Visual Fatigue Scale and Subjective Evaluation Questionnaire

The visual fatigue scale used in this study was adapted from the Rafael scale [42], which was primarily designed to assess visual fatigue caused by near work. The Rafael scale encompasses the evaluation of 7 symptoms, namely headaches, pain in the eyes, red eyes, blurred vision, double vision, burning eyes, and watery eyes. For this study, the scale was translated into Chinese. Based on the findings of the pre-experiment, dry eyes, and eye acidity, which were identified as common symptoms of visual fatigue, were included.

Likert scale levels, with scores ranging from "1: none" to "5: severe", were used to quantify the severity of nine symptoms (Scale S1).

The subjective questionnaire, which was completed online by the participants through their mobile phones, consisted of four parts (Questionnaire S1): basic information, luminous environment appraisal (rated on a Likert scale of 1–7, Table 3), the Karolinska Sleepiness Scale (KSS) (with scores ranging from "1: extremely alert" to "10: extremely sleepy, cannot keep awake"), and the pleasure-arousal-dominance (PAD) emotional state scale. The KSS is a widely accepted measure of arousal [43]. The PAD scale utilized a three-dimensional coordinate system to categorize emotions: "+P" and "−P" for pleasure versus displeasure, "+A" and "−A" for arousal and non-arousal, and "+D" and "−D" for dominance and submissiveness [44].

Table 3. The questions of the luminous environment appraisal part.

Questions	Likert Scale
Q1: Do you feel comfortable about the luminous environment?	"1: extremely uncomfortable" to "7: extremely comfortable"
Q2: Do your surroundings look attractive?	"1: extremely boring" to "7: extremely attractive"
Q3: How do you perceive the color of light?	"1: extremely unnatural" to "7: extremely natural"
Q4: How bright do you think the task area is?	"1: extremely dim" to "7: extremely bright"
Q5: How uniform do you think the brightness of the task area is?	"1: extremely ununiform" to "7: extremely uniform"
Q6: How bright do you think the surroundings are?	"1: extremely dim" to "7: extremely bright"
Q7: How strongly do you think the luminance contrast between the task area and surroundings is?	"1: uniform" to "7: strong contrast"
Q8: Do you feel any glares?	"1: feel no glare" to "7: unbearable"
Q9: Whether the reading material you see is clear?	"1: extremely ambiguous" to "7: extremely clear"

2.6.2. Visual Performance—Anfimov and Landolt Ring Test

Visual performance has been defined as the speed and accuracy of processing visual stimuli [29]. Common tests of visual performance include letter recognition (Anfimov table), number recognition, and pattern recognition (Landolt ring table). In this experiment, both the Anfimov table and the Landolt ring table were used (Tables S1 and S2). The Anfimov table consisted of the same number of letters A, B, C, E, H, K, N, and X in a random order, and all letters were printed in 13 pt Times New Roman font. Similarly, the Landolt ring table consisted of a random arrangement of the same number of Landolt rings with four gaps (top, bottom, left, and right), and the rings measured 7 mm × 7 mm. Participants were required to delete the assigned letter or the ring with the assigned gap within 2 min, respectively. They should practice these tests at least twice to counteract unfamiliarity before the experiment. In this study, the index of mental capability (IMC) was used to evaluate visual performance. It was calculated according to the following:

$$\text{IMC} = \frac{R}{2}\frac{D-E}{D}, \quad (1)$$

where R is the number of reading letters/rings, D is the number of letters/rings that ought to be deleted, and E is the number of errors and omissions [45].

Although the Anfimov test and Landolt ring test differed from some cognitive tasks, like the Stroop test and other tests used in previous studies [43,46], the Anfimov test and Landolt ring test still could reflect perception and memory based on four major functions: perception, memory and learning, thinking, and expression [10]. Moreover, these two tests were more suitable for paperwork.

2.6.3. Physiological Health—Heart Rate Variability

The emergence of wearable physiological monitoring systems has provided convenience for exploring physiological changes. In this study, electrocardiograph (ECG) signals were recorded using a chest strap sensor, and heart rate variability (HRV) analysis was conducted using ErgoLAB 3.0 software. HRV is the change in the time interval between adjacent heartbeats, which could reflect the decay of attention as a result of cognitive fatigue [47]. The root mean square of successive differences (RMSSD) is the primary time-domain measure, while the low frequency/high frequency (LF/HF) ratio is a frequency-domain measure to reflect heart rate variability. RMSSD is a sensitive indicator to assess the parasympathetic nervous system, and in general, HRV time-domain measurements decline with decreased health [48]. LF reflects the cardiac sympathetic nerve activity, while HF reflects the cardiac parasympathetic nerve activity. Therefore, the increase in LF/HF indicates an unstable autonomic balance and greater mental load, which may result from excessive pressure or fatigue. In this study, ECG signals recorded during the adaptation period were regarded as baseline data, and the final 5-min ECG signals during the reading period were regarded as post-test data.

3. Results

3.1. Descriptive Statistics

3.1.1. Mental Perception—Visual Fatigue

Before the reading task, the level of visual fatigue in Scene 3 (M = 0.19) was lower compared to the other three scenes. However, after reading, visual fatigue in Scene 2 (M = 1.57) became the most severe (Table 4).

Table 4. Descriptive statistics of visual fatigue before and after reading task.

	Pre-Test (Before Reading)				**Post-Test (After Reading)**			
	Min	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
Scene 1	0	6	0.81	1.47	0	4	1.10	1.09
Scene 2	0	3	0.67	0.86	0	5	1.57	1.63
Scene 3	0	1	0.19	0.40	0	4	1.14	1.39
Scene 4	0	3	0.67	0.91	0	4	1.05	1.24

3.1.2. Task Performance—Visual Performance

For the Anfimov test, the IMC was higher in Scene 1 (M = 351) and Scene 2 (M = 353), while the IMC was lower in Scene 3 (M = 330) and Scene 4 (M = 345) before reading. After reading, the IMC decreased to various degrees, except in Scene 3 (M = 340).

Regarding the Landolt ring test, the IMC was higher in Scene 2 (M = 245) and Scene 4 (M = 241), while it was lower in Scene 1 (M = 218) and Scene 3 (M = 206) before reading. However, the changes in IMC after reading varied across four lighting conditions. In Scene 1 (M = 220) and Scene 3 (M = 206), there was little change between the pre-test and post-test. Conversely, the IMC decreased in Scene 2 (M = 230), while the IMC increased in Scene 4 (M = 247).

3.1.3. Physiological Health—Heart Rate Variability

For RMSSD, there was no significant difference among the four lighting conditions, both before and after reading (Table 5). And the reduced range across four scenes after reading was similar, indicating that health declines were similar across the four scenes.

Table 5. Descriptive statistics of RMSSD before and after reading task.

	Pre-Test (Before Reading)				**Post-Test (After Reading)**			
	Min	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
Scene 1	16.4	86.4	45.6	19.35	21.1	73.9	43.0	17.89
Scene 2	11.3	91.8	43.7	20.32	14.0	94.4	40.4	22.27
Scene 3	13.3	93.9	43.1	21.02	15.7	86.7	42.1	18.01
Scene 4	9.4	94.7	44.9	23.60	13.3	84.3	40.1	19.53

For LF/HF, the initial LF/HF ratio was higher in Scene 3 (M = 1.4) and Scene 4 (M = 1.6), and lower in Scene 1 (M = 1.1) and Scene 2 (M = 1.2). After reading, a little increase can be found in Scene 3 (M = 1.6) and Scene 4 (M = 1.7), while a larger change can be found in Scene 1 (M = 1.9) and Scene 2 (M = 1.6).

3.2. Difference Analysis

3.2.1. Mental Perception—Visual Fatigue

Since ratings of visual fatigue were ordered categorical variables, paired-samples Wilcoxon signed-rank tests were used to analyze the changes in visual fatigue before and after reading (Table 6). The results showed that visual fatigue significantly increased in Scene 2 (z = 2.555, p = 0.011) and Scene 3 (z = 2.701, p = 0.007) (Figure 7). However, there was no significant difference in visual fatigue before and after reading in Scene 1 and Scene 4. Subsequently, the paired sample Wilcoxon signed-rank test was conducted to analyze the difference in the increment of visual fatigue between Scene 2 and Scene 3. The results indicated no significant difference between the two scenes ($p > 0.05$), suggesting that the degree of visual fatigue caused by both scenes was similar.

Table 6. Results of paired-samples Wilcoxon signed-rank tests.

	Paired Median (P_{25}, P_{75}) [1]		Median Difference(Pre-Test Minus Post-Test)	z-Value	p-Value
	Pre-Test	Post-Test			
Scene 1	0 (0, 1)	1 (0, 2)	−1	1.281	0.200
Scene 2	0 (0, 1)	1 (0, 3)	−1	2.555	0.011 *
Scene 3	0 (0, 0)	0 (0, 2)	0	2.701	0.007 **
Scene 4	0 (0, 1)	1 (0, 1)	−1	1.358	0.174

[1] P_{25} indicates the first quantile, representing about 25% of data points below this value. P_{75} indicates the third quartile, representing about 75% of data points below this value. * $p < 0.05$. ** $p < 0.01$.

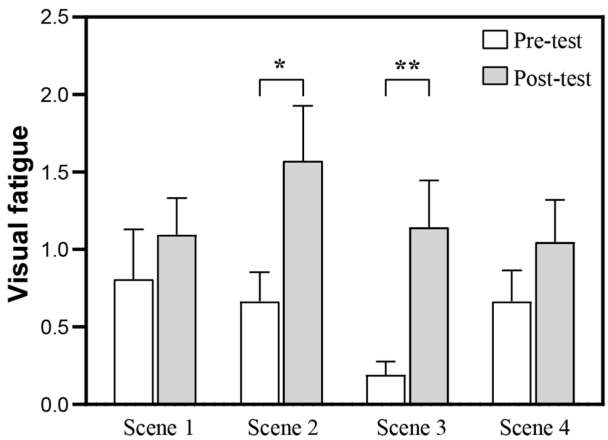


Figure 7. The changes of visual fatigue before and after reading in four scenes. The error line in the figure represents the mean standard error. **: $p < 0.01$; *: $p < 0.05$.

3.2.2. Mental Perception—Subjective Evaluation Questionnaire

- Luminous environment appraisal:

There were nine questions in this part. For each question, paired sample Wilcoxon signed-rank tests were conducted among the four scenes (Table 7). The results showed that participants perceived significantly higher comfort levels in Scene 4 compared to the other three scenes. Furthermore, the light color in Scene 4 appeared more natural than in the other three scenes. Additionally, in Scene 4, the task area exhibited the highest luminance uniformity and the least luminance contrast with its surroundings.

Table 7. The p-values of paired sample Wilcoxon signed-rank tests for luminous environment appraisal questions between scenes.

	1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
Q1: Do you feel comfortable about the luminous environment?	n.s. [1]	n.s.	0.034 (4) [2]	n.s.	0.049 (4)	0.033 (4)
Q2: Do your surroundings look attractive?	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Q3: How do you perceive the color of light?	n.s.	n.s.	0.019 (4)	n.s.	0.003 (4)	0.012 (4)
Q4: How bright do you think the task area is?	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Q5: How uniform do you think the brightness of the task area is?	n.s.	0.035 (3)	0.006 (4)	n.s.	0.017 (4)	n.s.
Q6: How bright do you think the surroundings are?	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Q7: How strongly do you think the luminance contrast between the task area and surroundings is?	n.s.	n.s.	0.030 (1)	n.s.	n.s.	n.s.
Q8: Do you feel any glares?	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Q9: Whether the reading material you see is clear?	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[1] n.s. represents no significant difference. [2] Specific p-values are written for $p < 0.05$, and the scene with a higher score is written in parentheses.

- Karolinska Sleepiness Scale (KSS)

For the KSS score, paired sample Wilcoxon signed-rank tests were conducted between scenes, and the results showed no significant difference in the degree of alertness among the four scenes ($p > 0.05$).

- PAD emotional state scale

Based on the PAD emotional state model, processed PAD values are shown in Table 8. These values showed that the emotional tendencies of the four scenes were all relaxed (+P − A + D) [44].

Table 8. PAD (pleasure-arousal-dominance) values in four scenes.

Scene	p Value	A Value	D Value
1	1.21	−0.79	0.14
2	1.12	−1.40	0.14
3	1.40	−0.81	0.62
4	1.76	−1.12	0.24

3.2.3. Task Performance—Visual Performance

The Shapiro–Wilke normality test was used to assess the normality of the difference in IMC (the index of mental capability) before and after reading, thereby determining the appropriate analytical approach for each scene. For the Landolt ring test in Scene 2, which failed to conform to a normal distribution, the Wilcoxon signed-rank test was used. Conversely, the paired sample T-test was applied to the other situations. The results showed no significant change in the IMC of the Anfimov test in any scene ($p > 0.05$), while the IMC of the Landolt ring test decreased significantly in Scene 2 ($z = 2.172$, $p = 0.03$) (Figure 8). Although both tests measure attention level, disparities in results suggest that distinct visual characteristics of the tests contribute to different information processing challenges and sensitivities to lighting conditions.

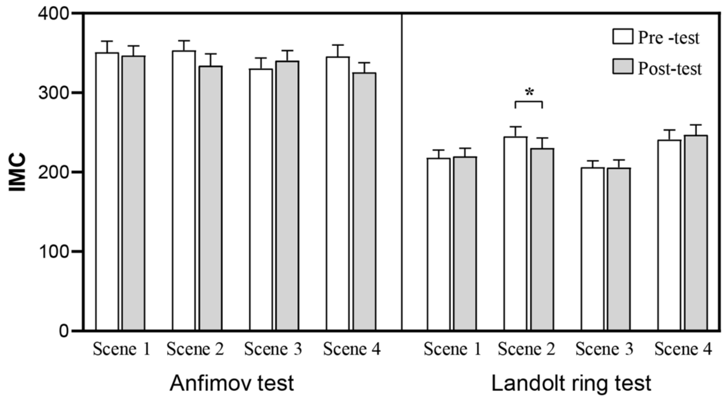


Figure 8. The changes in visual performance in four scenes. The error line in the figure represents the mean standard error. *: $p < 0.05$.

3.2.4. Physiological Health—Heart Rate Variability

For RMSSD and LF/HF, the baseline data and post-test data were obtained through ErgoLAB (Kingfar, Beijing, China). Based on the Shapiro–Wilke normality test, the paired sample Wilcoxon signed-rank test was applied to RMSSD in Scene 2, and LF/HF in Scene 1 and Scene 3. The remaining data were analyzed using paired sample T-tests. The results showed that RMSSD significantly declined in Scene 2 ($z = 2.068$, $p = 0.039$), indicating declining health. And LF/HF significantly increased in Scene 1 ($z = 2.555$, $p = 0.011$) and Scene 2 (t (20) = -2.265, $p = 0.035$), indicating an unstable autonomic balance and greater mental load (Figure 9). Subsequently, a paired sample T-test was conducted to analyze the difference in increment in LF/HF between Scene 1 and Scene 2. The results indicated no significant difference between the two scenes ($p > 0.05$), suggesting that the increment in LF/HF caused by both scenes was similar.

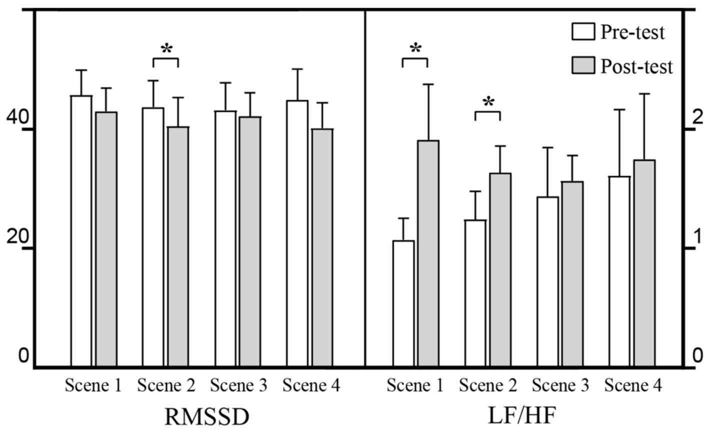


Figure 9. The changes of RMSSD and LF/HF in four scenes. The error line in the figure represents the mean standard error. *: $p < 0.05$.

3.3. Summary of Results

The results were summarized (Table 9). People performed best in Scene 4, with no deterioration observed in any of the indicators following the reading. Conversely, Scene 2 showed the poorest comprehensive performance, reflected by the significant increases in visual fatigue and LF/HF and the significant decreases in IMC of the Landolt ring test and RMSSD. Both Scene 1 and Scene 3 had a significant effect on one indicator, respectively. To be specific, there was an increase in steady-state load in Scene 1 and an increase in visual fatigue in Scene 3.

Table 9. Summary of the results.

		Scene 1	Scene 2	Scene 3	Scene 4
Mental perception	Visual fatigue	- [1]	↑ [2]	↑	-
	Luminous environment appraisal	-	-	-	☆ [3]
	KSS	-	-	-	-
	PAD	-	-	-	-
Visual performance	Anfimov test	-	-	-	-
	Landolt ring test	-	↓ [4]	-	-
Phycological health	RMSSD	-	↓	-	-
	LF/HF	↑	↑	-	-

[1] "-" indicates that the indicator has no significant change in this scene or has no significant advantage over other scenes. [2] "↑" indicates a significant increase in visual fatigue or LF/HF. [3] "☆" indicates that the scene is significantly better than others. [4] "↓" indicates a significant decrease in IMC or RMSSD.

4. Discussion and Conclusions

The current study investigated whether various eye illuminance distributions in the horizontal FOV would affect human performance. These findings suggest that eye illuminance distribution plays a significant role in visual fatigue, Landolt ring performance, heart rate variability, and the appraisal of a luminous environment. Specifically, Scene 4 (E_{ec} = 186 lx, distribution pattern = "m" shape) was superior in sustaining human performance. In contrast, human performance significantly declined in Scene 2 (103 lx, "m" shape).

In the present experiment, the significant increase in visual fatigue observed in Scene 2 (103 lx, "m" shape) and Scene 3 (192 lx, "C" shape) cannot be explained by previous studies, which suggested more visual fatigue observed in a dark environment compared to illuminated environments [49,50]. This indicates that visual fatigue is affected not only by light level but also by a complex interaction between light level and light distribution. Moreover, E_v (vertical eye illuminance) values can predict and evaluate visual comfort or discomfort in various daylit conditions [51]. Hence, the results of visual fatigue may be related to non-visual effects, and more research on the relationship between E_v and visual fatigue is needed. In addition, the increase in positive luminous environment appraisal in Scene 4 (186 lx, "m" shape) further emphasizes the primary effect of illuminance on satisfaction. This is consistent with previous research showing that higher illuminance levels correspond with more positive lighting satisfaction [10,52].

The study found that the four scenes had no significant effect on letter recognition (Anfimov test), while the pattern recognition (Landolt ring test) ability was significantly decreased in Scene 2 (103 lx, "m" shape). Pattern recognition requires higher visual processing capacity than letter recognition, possibly reflecting a higher dependence on light quality for complex visual tasks. This finding is consistent with prior research that suggests various tasks reflecting brain functions could be impacted by different lighting factors [10]. Therefore, lighting design needs to consider task characteristics to obtain the best visual performance.

The mental load significantly increased in Scene 1 (103 lx, "C" shape) and Scene 2 (103 lx, "m" shape). These changes suggest that the decrease in eye illuminance in the horizontal FOV may contribute to the increase in mental load. However, it is crucial to note that an excessively high mental load can induce stress, while an overly low mental load may lead to sleepiness [53]. Therefore, the good lighting conditions for home learning should not be judged based on mental load.

The incident direction of the light on task may also influence human performance. In this experiment, although the task illuminance was kept at 500 lx, the ratio of task lighting from the desk lamp to the ceiling lamps would have an impact. In Scene 1 and Scene 2, two-thirds of the light on task comes from the desk lamp at a mirror angle, which may reduce the contrast of printed letters and subsequently affect human performance or comfort. Therefore, the task lighting conditions in this study may also affect participants' performance and responses.

This study proposes Scene 4 (186 lx, "m" shape) as a relatively better lighting condition. However, it should be noted that current findings are limited to paper-based tasks under the four lighting conditions used in this study, and therefore, they cannot be generalized to other lighting patterns or VDT tasks. Further studies on lighting conditions around Scene 4 (186 lx, "m" shape) are needed to investigate the optimal lighting condition and the underlying mechanisms behind the effects. Additionally, the position of the luminaires in this study may not be common in reality, where the ceiling light might be centrally located within the space and behind the subjects. Given that centrally located ceiling lights may result in different light shades for individuals, it is challenging to control lighting conditions that reach the task area or the eyes. Hence, the position of the ceiling light was chosen to be above the desk, although this may limit the generalizability of the findings to typical lighting patterns in reality. This paper discusses the importance of considering the distribution of eye illuminance in the horizontal FOV rather than focusing solely on the illuminance directed perpendicularly into the eye from the front. It emphasizes the need to account for both central and peripheral vision. Furthermore, the discoveries also contribute valuable insights to lighting design practices and offer a new perspective for investigating the relationship between vision lighting, vision neuroscience, and non-visual effects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14051456/s1, Questionnaire S1: Subjective evaluation questionnaire; Scale S1: Visual fatigue scale; Table S1: Anfimov table; Table S2: Landolt ring table.

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Glossary

FOV	Field of view. This paper only deals with the horizontal field of view.
Central FOV	Central 120 degrees of the visual angle around the point of fixation, corresponding to central vision.

Peripheral FOV	The part of FOV that extends beyond the central FOV, corresponding to peripheral vision.
E_v	Vertical eye illuminance. It refers specifically to the illuminance entering the eye vertically from directly in front of the eye in this paper.
E_{ec}	Average eye illuminance of central FOV.
E_{ep}	Average eye illuminance of peripheral FOV.

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