

Article

Effects of Key Lighting Parameters on Visual Fatigue Among Secondary School Students in VDT-Equipped Multimedia Classrooms

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Abstract

Visual fatigue is a serious issue among Chinese secondary school students owing to prolonged daily exposure (8–10 h) to visual display terminals (VDTs) in widely equipped multimedia classrooms. To mitigate such effects, this exploratory study identifies promising lighting parameters by evaluating the influence of blackboard reflection coefficients, the ratio of desktop illumination to blackboard illumination, and correlated color temperature (CCT) in a simulated multimedia classroom environment. Thirteen participants performed visual tasks (Landolt ring visual acuity tests and Anfimov's Chart Task) under various conditions. Visual fatigue scale (VFS-10), index of mental capacity (IMC), and eye movement parameters (EMP) were used to assess visual fatigue and efficiency. Results suggest that higher blackboard reflection coefficients improved efficiency and reduced fatigue. Increased blackboard illumination alleviated fatigue at constant CCT, whereas changes in desktop illumination showed no significant effect. The highest efficiency among the tested CCT values was observed at 4700 K, while visual fatigue was minimized at 4000 K. The findings provide preliminary practical applications for minimizing visual fatigue and improving performance efficiency in secondary school multimedia classroom environments equipped with VDTs.

Keywords: multimedia classroom lighting environment; lighting and health; visual display terminal; visual fatigue; visual task; eye movement parameters



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1. Introduction

Visual fatigue has emerged as a major health concern among secondary school students in China, primarily resulting from prolonged daily exposure to interactive electronic whiteboards (EWBs) in multimedia classrooms [1–8]. These facilities now exceed 98.35% penetration nationally, with students spending 8–10 h per day in such environments [9–11]. EWB based instruction occurs in approximately 85% of classes, yet conventional classroom lighting standards remain misaligned with modern VDT dependent teaching practices [10].

During this critical developmental period, adolescents exhibit heightened ocular sensitivity to inadequate lighting [10–13].

Cumulative visual fatigue, caused by insufficient lighting on multiple visual targets including electronic whiteboards, blackboards, and desks, impairs vision and lowers learning efficiency. Population based studies have documented the secular decline of visual acuity among Chinese primary and secondary school students over decades [14–16]. Laboratory experiments comparing computer versus paper-based tasks have identified differences in working memory performance [17,18] and visual fatigue in elementary school students during ebook reading [19,20]. Field studies utilizing teacher interviews have reported potential adverse health outcomes associated with digital textbook use in classrooms [21,22], while experimental research on VDT operators has established early links between visual fatigue and occupational stress [23,24].

Furthermore, extended VDT use is associated not only with decreased productivity and physiological decline [18,22,25] but also with potential mental health issues [26,27]. Laboratory studies on adult VDT operators have documented physiological responses including decreased pupillary reflexes and accommodative function [28], as well as disruptions to melatonin secretion, core body temperature, and heart rate during night time VDT tasks [28,29]. Observational studies in working populations have identified VDT use as a risk factor for dry eye disease [30,31] and have demonstrated associations with physical symptoms, binocular vision dysfunctions, and work productivity loss [31,32]. Psychosocial research has further linked prolonged VDT work to employee mental health concerns [26], a finding corroborated by recent studies among healthcare workers and during COVID-19 lockdowns [33,34]. Therefore, there is an urgent need to systematically investigate and optimize classroom lighting parameters tailored to VDT based learning environments.

Although extensive research has explored VDT induced visual fatigue, most studies have focused on adult office settings rather than educational environments for adolescents. A seminal 1980s study by Marvin et al. [23] established the high prevalence of visual fatigue among visual display terminal (VDT) workers. Subsequently, research since the mid-1990s has focused on devising evaluative metrics and mitigation strategies for visual fatigue induced by VDT. This research has also delved deeper into the correlation between VDT usage and the incidence of visual fatigue. Specifically, Shi et al. [24] employed eye movement parameters to quantify visual fatigue in VDT operations, finding that its severity increases with the duration of VDT use.

Beyond usage patterns, the physical lighting environment itself, particularly its interface reflection properties, has been identified as a key factor influencing visual comfort in educational contexts. Scholarly attention has increasingly focused on the importance of interface reflection coefficients in multimedia classroom environments. Mao et al. [35] used a multimedia classroom in a college in Zhejiang, China as the research object and tested five different types of light environment scenes in the multimedia classroom. The results indicate that the overall visual satisfaction of the classroom is low, especially when the blackboard and classroom materials are designed with a dark background. Cai et al. [36] conducted simulations using DIALux lighting design software to compare fluorescent and LED lighting systems. Their analysis demonstrated that different interface reflection coefficients and light distribution methods should be considered to optimize the lighting design scheme.

In addition to reflection properties, illumination and correlated color temperature are equally critical components of artificial lighting in multimedia classrooms. Li et al. [37] evaluated the illumination elements of desktop illumination, blackboard illumination, and projection curtain brightness in multimedia classrooms in colleges and universities, finding that projection curtain illumination frequently affects the illumination of the blackboard

due to their proximity. In an experimental study of Shanghai primary and secondary schools, Lin et al. [38] demonstrated that CCT, illumination, and environmental contrast significantly influence the level of visual fatigue. Huang [39] conducted an analysis of students' subjective perceptions of classroom lighting CCTs and reported that a moderate CCT was generally perceived as the most comfortable. However, the effect of very high CCT (e.g., above 6500 K) on visual fatigue is more complex: such CCTs can suppress melatonin secretion, which may temporarily reduce the subjective feeling of fatigue, while visual discomfort depends strongly on the illuminance level [40]. Therefore, the claim that high CCT directly increases fatigue is incomplete without considering illuminance.

Recent international studies have further confirmed these findings. Chen et al. conducted a self-controlled study with 22 young adults [41]. They found that both illuminance (300 lx to 1000 lx) and correlated color temperature (2700 to 6500 K) of LED lighting clearly affected asthenopia during reading tasks lasting two hours, with higher CCT making subjective visual fatigue worse. Bao et al. [42] reported that putting full spectrum indoor lighting in classrooms slowed myopia progression in children of school age over 12 months, which points to the broader importance of lighting quality for adolescent visual health. Xu et al. [43] carried out longitudinal field research and showed that classroom daylighting had lasting effects on students' visual comfort. Wang et al. [44] also linked semicylindrical illuminance to reading distance and myopia prediction in adolescents.

Importantly, in multimedia classrooms, VDTs and the surrounding environment collectively constitute an integrated visual work surface [45], creating a unique visual challenge. As instructors alternate between screens and blackboards, students must continuously refocus on VDTs, blackboards, desktops, and other objects. The inherent self-illumination and high brightness of VDTs contrast sharply with the reflective properties of traditional surfaces. This discrepancy forces the human visual system to undergo constant adaptation to drastically varying luminance levels, leading to frequent pupil and photoreceptor adjustments that culminate in visual fatigue. Thus, the classroom luminous environment must be designed to harmonize these disparate visual targets, rather than treating them in isolation.

Despite recognizing this complexity, current research fails to provide integrated solutions. First, most studies on VDT induced visual fatigue have focused on adult office environments, lacking dedicated investigation into adolescent students in educational settings. Second, existing research tends to examine single lighting parameters (e.g., illumination or CCT) independently, neglecting their necessary synergistic effects within a real classroom. Finally, conventional approaches often treat the VDT and the surroundings as separate visual targets. This fragmentation ignores the reality of a multimedia classroom, where VDTs, blackboards, and desktops collectively form a single, continuous visual environment. In this setting, students must continuously shift their gaze across all of these surfaces. Consequently, the combined impact of key optical parameters on adolescent visual fatigue in authentic, interactive learning environments remains severely underexplored.

Several factors can cause visual fatigue in multimedia classrooms, including flicker from lights, the way color temperature and brightness work together, high luminance contrast, prolonged near work, and personal factors like age and gender. In this study, we controlled or set aside some of these factors so we could focus on blackboard reflectance, the lighting ratio between desk and board, and color temperature. We checked our LED fixtures and found no flicker. The Kruithof interaction was not fully examined because we varied both illuminance and CCT as separate factors. These points are discussed as limitations later in the paper.

Therefore, this study aims to bridge these gaps by systematically investigating the combined effects of key lighting parameters, namely blackboard reflection coefficient, the ratio of desktop illumination to blackboard illumination, and correlated color temperature,

on visual fatigue and cognitive performance in a simulated secondary school multimedia classroom environment.

To reliably quantify visual fatigue, which manifests primarily as visual deterioration and compromised work efficiency, a multiple method assessment approach is essential. Therefore, this study employed three complementary metrics to capture these distinct manifestations: (1) the Visual Fatigue Scale (VFS-10) [45] to quantify subjective symptoms of visual impairment and discomfort; (2) eye movement parameters (EMP) [46–49] to provide objective physiological indicators of oculomotor strain associated with visual function; and (3) the index of mental capacity (IMC) to directly assess task performance efficiency, thereby evaluating the impact of fatigue on work efficacy [49,50].

This study aims to address the empirical research gap in coordinated lighting design guidelines for multiple target visual areas (electronic whiteboards, blackboards, and student desks) within secondary school multimedia classrooms. By quantifying the interplay between visual fatigue and two critical factors, chalkboard background reflectance and lighting conditions (including illuminance levels and correlated color temperature), we establish VDT task specific optimization criteria for the luminous environment. Using a comparative methodology, we measured subjective visual fatigue, mental capacity indices, and eye movement parameters before and after experimental interventions. The research focused on three critical parameters in multimedia classroom VDT environments: blackboard reflection coefficient, the ratio of desktop illumination to blackboard illumination, and light source CCT. Visual tasks including Landolt ring visual acuity tests and the Anfimov's Chart Task were employed to assess visual fatigue levels. This comprehensive approach promises to shed light on the multifaceted factors influencing visual fatigue in secondary school multimedia classroom settings.

2. Materials and Methods

The experiment is composed of two principal parts. The first part investigates the impact of the blackboard's reflection coefficient on student visual fatigue. The second part seeks to determine the influence of the illumination ratio and the CCT of the light source on this fatigue.

In Part 1, the blackboard's background reflection coefficient was investigated as an independent variable influencing visual fatigue. To assess the impact of different blackboard reflection coefficients on students' visual fatigue, desktop, blackboard, and electronic whiteboard illumination were maintained at uniform levels. A multifaceted evaluation approach was employed, incorporating subjective fatigue scales, visual performance tests, and eye movement parameters to quantify the physiological response to visual fatigue. This comprehensive methodology ensures a nuanced understanding of how these environmental factors influence visual fatigue among students.

Part 2 of this study aimed to ascertain the favorable illumination levels and light source CCT within the tested conditions for work surfaces under conditions of VDT usage in multimedia environments. This investigation established the ratio of desktop illumination to blackboard illumination and light source CCT as key experimental parameters. Utilizing a combination of subjective fatigue scale, performance tests, and eye movement parameters, we assessed how these lighting conditions affect visual fatigue and work efficiency. This comprehensive assessment approach provides valuable insights into lighting conditions that appeared most conducive within the experimental setup to reduce visual fatigue while enhancing productivity in educational settings.

2.1. Environmental Settings

2.1.1. Part 1: Experiment on the Effect of Blackboard Reflection Coefficient on Students' Visual Fatigue

The experimental setup was established in the optical laboratory at Chongqing University. To eliminate interference from natural light, blackout curtains and sliding blackout panels were installed around the laboratory windows and the lighting simulation area. The illumination simulation area was furnished with tables and chairs to replicate a classroom environment.

The simulation area was designed to replicate a standard Chinese secondary school multimedia classroom at a geometrically scaled ratio of 0.166. This ratio was derived from the actual classroom dimensions (9.6 m length $\times$ 7.2 m width) and the typical viewing distance from the center of the classroom to the blackboard (4.8 m), resulting in the simulated environment dimensions summarized in Table 1. A Dell UltraSharp U2417H monitor (manufactured by Dell Inc., Round Rock, TX, USA; luminance: 345.66 cd/m², CCT: 8835 K, Ra: 84.8, CQS: 85.8) served as a surrogate for the electronic whiteboard, positioned at an ergonomically scaled viewing distance of 0.8 m from the participant. CQS (Color Quality Scale) is a metric that evaluates the color rendering quality of a light source, complementing the traditional color rendering index Ra; it is reported here solely to characterize the display's optical properties and was not treated as an experimental variable. Adjacent to the monitor, a printed paperboard simulating the traditional blackboard was installed.

Table 1. Simulated Environment Dimensions.

Parameter	Real Environment Dimensions	Simulated Environment Dimensions
Classroom Length	9.6 m	1.6 m
Classroom Width	7.2 m	1.2 m
Blackboard Length	2.0 m	0.333 m (33.3 cm)
Blackboard Width	1.2 m	0.2 m (20.0 cm)
Viewing Distance (Participant to Blackboard)	4.8 m	0.8 m (80.0 cm)

To maintain consistent visual angles with real classroom conditions, the character size displayed on the simulated blackboard was determined based on the standard character height of 10 cm viewed from 4.8 m (resulting in a visual angle of approximately 1.19°) [51]. Accordingly, a character height of 1.66 cm was used in the simulated setting (viewing distance: 0.8 m) to ensure that the visual task demands accurately represented actual educational scenarios.

Illumination was provided by two sets of LED light sources (CCT: 4003 K, Ra: 89.2, and CQS: 86.5). The LED sources operate at 1200 Hz with a modulation depth of 11.34%, well below the IEEE 1789-2015 [52] “no effect” limit, confirming they are flicker-free. One was parallel to the desktop surface and the other was directed at the paperboard. In this experimental configuration, the measured parameters included desktop reflection coefficient of 0.51, horizontal illumination of 300 lx, and vertical illumination on the printing paperboard of 500 lx. All lighting parameters adhered to specifications outlined in the Architectural Lighting Design Standards (GB/T 50034-2024) [51]. Figure 1 illustrates the experimental configuration, while Table 2 provides comprehensive specifications of the light source parameters.

The primary experimental variable was the reflection coefficient of the blackboard background, simulated using paperboards. To represent typical classroom blackboard and desktop backgrounds, three types of paperboards were selected: white with black text, green with white text, and black with white text. All paperboards were printed with identical Landolt Ring Visual Acuity charts and Anfimov's Vision chart, with uniform content and font size, to ensure consistent stimulus presentation throughout the experiment. The measured reflection coefficients were 0.61 for the white paperboard, 0.16 for the green paperboard, and 0.09 for the black paperboard, with parameters outlined in Table 3.

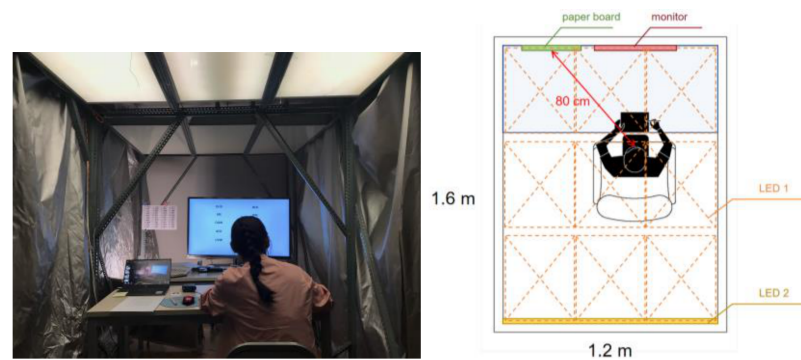


Figure 1. Environmental settings.

Table 2. Light source parameter settings.

Light Source	Luminance	CCT	Ra	CQS
Monitor	345.66 cd/m ²	8835 K	84.8	85.8
Led Fixture (Desktop)		4003 K	89.2	86.5
Led Fixture (Paperboard)		4003 K	89.2	86.5

Table 3. Physical parameters of the experimental environment (Experiment 1).

Paperboard Color	Reflection Coefficients
white	0.61
green	0.16
black	0.09

It should be noted that the three paperboard conditions differed in contrast polarity (white and green: positive polarity; black: negative polarity), in addition to reflectance. However, based on visual psychophysics literature [53,54], contrast polarity is not a primary factor in Landolt C orientation discrimination tasks compared to luminance contrast, which is determined by reflectance.

2.1.2. Part 2: Experiment on the Effect of Illumination Ratio and Color Temperature of Light Source on Students' Visual Fatigue

In the experimental setup for Part 2, the blackboard was simulated utilizing a white paperboard printed with a performance test. This design was based on Part 1's findings, where white paperboard optimized work efficiency. Figure 2 illustrates the research framework and the relationship between experimental Part 1 and Part 2. The illumination ratios between classroom desks and blackboard were set based on Part 1's reflection coefficient results. Desktop illumination levels were set at 300 lx and 500 lx, and blackboard illumination levels at 500 lx and 750 lx, in compliance with the Architectural Lighting Design Standards. Three correlated color temperatures (3300 K, 4000 K, and 4700 K), representing warm, neutral, and cool lighting conditions, were tested. This resulted in 12 lighting conditions, with detailed parameters outlined in Table 4.

Table 4. Physical parameters of the experimental environment.

Illumination Ratio				
CCT	300 lx × 500 lx	300 lx × 750 lx	500 lx × 500 lx	500 lx × 750 lx
3300 K	3300 × 300 × 500	3300 × 300 × 750	3300 × 500 × 500	3300 × 500 × 750
4000 K	4000 × 300 × 500	4000 × 300 × 750	4000 × 500 × 500	4000 × 500 × 750
4700 K	4700 × 300 × 500	4700 × 300 × 750	4700 × 500 × 500	4700 × 500 × 750

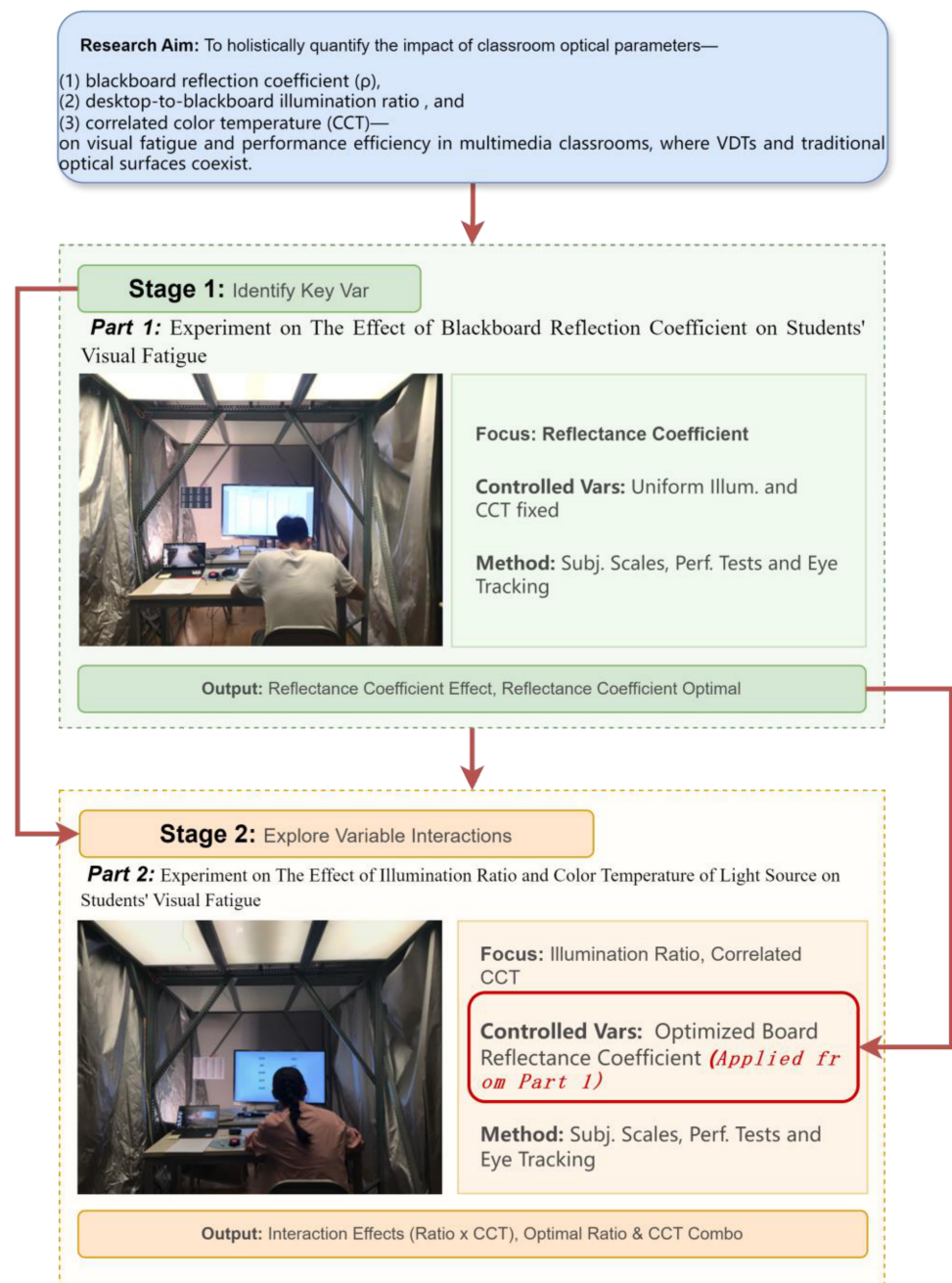


Figure 2. Research framework.

2.2. Subjects

The study involved 13 secondary school students, five males and eight females, aged between 12 and 18 years. All participants had normal color vision, no history of eye diseases, and no refractive errors other than myopia (i.e., no astigmatism or hyperopia). Their visual acuity was 5.0 (equivalent to 1.0 on the Snellen scale) in each eye, either naturally or with correction. To reduce potential confounding factors, participants were instructed to avoid consuming coffee, tea, and other central nervous system stimulants for 12 h before the experiment.

2.3. Data Acquisition Method

Visual fatigue arises from retinal fatigue or coordination fatigue, both linked to diminished performance of ocular muscles or brain [53]. To assess these distinct etiologies, we employed subjective methodologies (VFS-10) and eye movement parameters (EMPs)

to quantify muscular performance reduction, indicating retinal fatigue. Meanwhile, we utilized subjective assessments and alterations in cognitive performance (IMC) indices to gauge the decline in brain function, thereby reflecting the severity of coordination fatigue. To illustrate how the three methods complement each other, their key distinctions and interrelationships are summarized in Table 5.

Table 5. Comparison of Three Visual Fatigue Evaluation Methods.

Evaluation Methods	Visual Fatigue Scale (VFS-10)	Eye Movement Parameters (EMPs)	Index of Mental Capability (IMC)
Nature of Assessment	Subjective Assessment	Objective Measurement	Cognitive Performance
Dimension Captured	Self-reported Symptom Intensity	Neuromuscular Regulation (Retinal Level)	Central Coordination Fatigue & Information Processing Capacity
Primary Data Source	Participant Self-reports	Quantification of Biomarkers (via eye-tracker)	Task Performance Degradation
Primary Focus	Perceived severity of symptoms	Physiological control mechanisms	Efficiency of higher cognitive function
Complementary Relationship	The three methods are mutually complementary, capturing three distinct but critical dimensions of visual fatigue: subjective perception, physiological mechanisms, and central cognition. Together, they form a comprehensive assessment framework.		
Integrated Value	This enables cross validation. A multiple dimensional approach overcomes the inherent limitations of any single method assessment, such as bias in subjective reports or objective metrics that do not fully capture subjective experience. This leads to more accurate and reliable diagnosis.		
Common Goal	To comprehensively and accurately evaluate the pathophysiological dimensions of visual fatigue for research, diagnosis, and intervention.		

2.3.1. Subjective Methodology

The subjective assessment of visual fatigue was conducted utilizing the Visual Fatigue Scale (VFS-10) [35,39,45]. Throughout the experimental procedure, participants were required to complete the VFS-10, and the difference between their scores before and after the experiment was used as an indicator of visual fatigue changes.

2.3.2. Physiological Methodology

Eye movement parameters (EMP) were utilized as the physiological assessment tool in this study. Eye movements, biological indicators of physiological states, were measured using wearable eye tracking devices. The primary parameters analyzed included saccadic metrics, fixation stability, and pupil diameter changes, all of which are sensitive markers of fatigue. To ensure data accuracy and reliability, eye tracking devices with a minimum sampling rate of 250 Hz were considered. Sampling rates below 250 Hz may result in critical data loss, compromising the measurement of these subtle dynamics. Previous research has established 250 Hz as the minimum standard for precise analysis of saccadic behavior, fixation stability, and pupil dynamics in fatigue-related studies.

2.3.3. Index of Mental Capability

In this study, we incorporated objective assessment methods, namely Landolt ring visual acuity test and the Anfimov's Chart Task, to evaluate cognitive performance. To replicate a working environment where VDT and surrounding context are visual surfaces, the Landolt C checklist and the word lookup table were presented on the VDT and a

printout board. Participants had to alternate their gaze between the VDT and the printout board to complete the search tasks. The index of mental capability was utilized to measure the students' work efficiency throughout the experiment.

2.3.4. Equipment

The experiment leveraged Tobii Pro Glasses 2 (manufactured by Tobii AB, Stockholm, Sweden), a sophisticated eye tracking device, to capture eye movement parameters. Throughout the study, this device provided a real-time record of the subjects' visual engagement, capturing every detail of their visual journey. The corresponding eye tracking data were subsequently processed with specialized software to extract the requisite eye movement parameters for analysis.

2.4. Experimental Materials

2.4.1. Subjective Fatigue Scale

- VFS-10 (Visual Fatigue Scale)

We used the VFS-10 to measure the main signs of visual fatigue. This scale is instrumental in determining the presence and severity of visual fatigue in subjects. It enumerates ten principal symptoms of visual fatigue, each classified into six severity levels. A subject is deemed to be experiencing visual fatigue when exhibiting two or more of these symptoms concurrently. Refer to the Supplementary Materials.

2.4.2. Task Test

- Landolt Ring Visual Acuity Test

The Landolt ring visual acuity test is a standardized visual acuity test that requires participants to identify the coordinates of visual markers aligned with the orientation of a specified aperture on the Landolt C checklist. This task is designed to evaluate the participants' visual performance through dual metrics: task completion accuracy and mental capability indices. These metrics collectively provide insights into the participants' visual efficacy and visual fatigue during sustained visual tasks. The font size is proportionally scaled for an 80 cm viewing distance. Refer to the Supplementary Materials.

- Anfimov's Chart Task

The Anfimov chart task is a tool utilized in ophthalmology and optometry for visual acuity examination. This experiment employed a triple-surface adaptation of the Anfimov task, utilizing target words displayed on the electronic whiteboard, a cipher table on the blackboard mapping words to specific letters, and abbreviated Anfimov charts on the desktop. Participants were required to sequentially identify the target word on the whiteboard, locate its corresponding cipher letter on the blackboard, and then cancel all instances of that letter in the desktop Anfimov chart within a defined time limit. This task was structured in a cyclic dosing format, necessitating sequential visual switching between the electronic whiteboard, blackboard, and desktop surfaces, thereby accurately replicating the oculomotor pathways characteristic of multimedia classroom environments. Participant performance was evaluated by measuring reading speed and error rates, with results serving as indicators of ocular muscle fatigue and reduced work efficiency, both constitutive dimensions of visual fatigue. Refer to the Supplementary Materials.

2.5. Experimental Procedure

2.5.1. Experimental Procedure of Part 1

In this study, each participant completed three experimental conditions in a randomized order to minimize order effects and reduce potential errors. These conditions varied

according to the use of a whiteboard, greenboard, and blackboard. To mitigate participant fatigue, a rest interval of 10 min was provided between each experimental session. The task duration for each experimental condition was rigorously maintained for all participants. To ensure this, a fully automated computer protocol delivered the instructions and controlled the pacing, guaranteeing identical exposure times. The detailed experimental procedure is as follows:

Step 1: Orientation and Initial Assessment. Participants received comprehensive briefing regarding experimental protocols and task requirements, followed by completion of preliminary assessment scales.

Step 2: Eye tracking Device Setup. Participants were fitted with the Tobii Pro Glasses 2 eye tracking device, and calibration was performed to ensure accurate tracking of visual focus.

Step 3: Baseline Visual Fatigue Assessment. Participants completed the VFS-10 to assess their initial levels of visual fatigue and sleepiness before the experiment. (5 min)

Step 4: Landolt ring visual acuity test. Participants engaged in a visual acuity task requiring identification of aperture orientations in the Landolt C checklist by locating specific visual markers on the printed board. (1 min)

Step 5: Anfimov's Chart Task. Participants were required to identify matches between target words displayed on a VDT and their corresponding serial numbers on the printed board, sequentially recording these identifications on a designated record sheet until all 40 words were processed. (5 min)

Step 6: Post Task Visual Acuity Test. The visual acuity test was repeated to assess any changes in participants' ability to identify the coordinate positions of visual markers. (1 min)

Step 7: Post Experimental Visual Fatigue Assessment. Participants retaken the VFS-10 to measure changes in visual fatigue after each task.

A rest interval of 10 min was provided after each session. This process was repeated for the remaining two experimental conditions, each involving different reflectance coefficients of the boards, until all three conditions were completed.

2.5.2. Experimental Procedure of Part 2

Participants engaged in three primary experimental groups, each consisting of four subordinate sessions. To ensure sufficient recovery and minimize carryover fatigue effects, a break of 10 min was scheduled between every two subordinate sessions, and a break of 20 min was allotted between each primary group. The experimental procedure was as follows:

Steps 1 and 2: These initial steps replicated the procedures outlined in Part 1, thereby ensuring methodological consistency.

Steps 3 to 5: These steps were analogous to steps 4 to 6 in Part 1, maintaining continuity across experimental conditions.

Step 6: Intermediate Rest Period. Following the completion of the first subordinate session, a rest period of 5 min was provided to alleviate immediate fatigue.

Steps 7: Repetition of Subordinate Sessions. Steps 3 to 6 were repeated three times to complete the first primary group. A break of 20 min was subsequently provided for comprehensive recovery.

Steps 8: Completion of Remaining Groups. Participants repeated steps 2 through 7 for the remaining two primary groups, culminating in the completion of all experimental sessions.

The experimental design for both Part 1 and Part 2 is summarized in Figure 3.

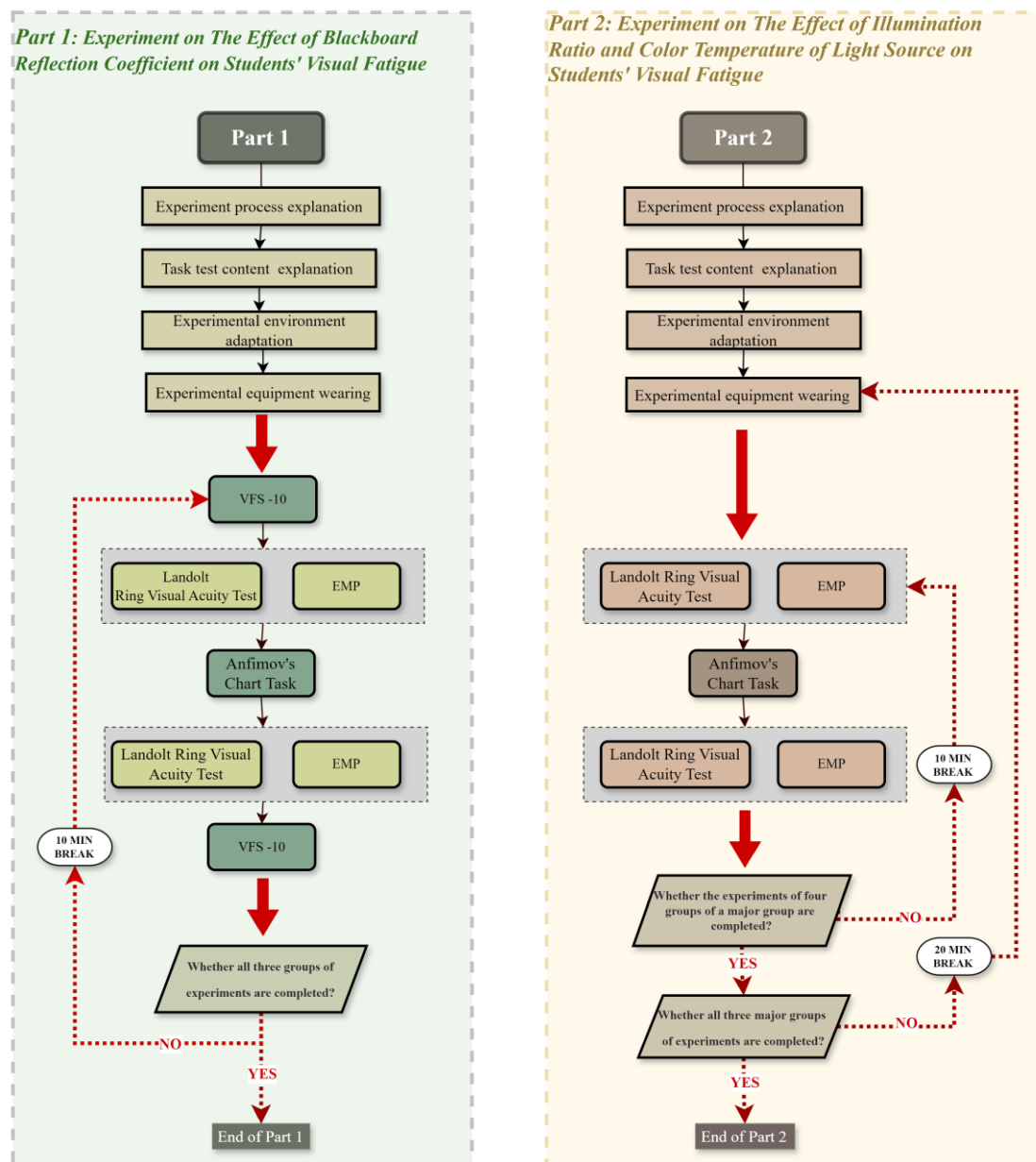


Figure 3. Experimental flowchart.

2.5.3. Methodological Controls for Experimental Errors

To ensure the reliability of the experimental results, several methodological controls were implemented to minimize potential confounding factors. First, to control for environmental adaptation effects, participants were given 30 min to acclimate to the laboratory environment before the start of the experiment. When experimental conditions changed between sessions (e.g., variations in blackboard reflectance or lighting parameters), a period of 2 min adaptation period was provided after each rest interval to allow participants to adjust to the new lighting environment before commencing the visual tasks.

Second, to account for individual differences in baseline eye movement levels and cumulative fatigue across sessions, a within-subject control design was employed. At the beginning of each experimental session, baseline parameters were measured under controlled conditions. After completing the experimental tasks, post task measurements were taken, and the change values, calculated as post task minus baseline, were used as the dependent variables for analysis. This approach isolates the fatigue effects attributable to the experimental conditions from individual variability and order related fatigue accumulation.

Third, the order of experimental conditions was randomized across participants to minimize order effects. For Part 1, the three paperboard colors (white, green, and black) were presented in randomized order. For Part 2, the three experimental groups with different illumination ratios and CCT were also randomized. Additionally, 10 min of rest intervals were scheduled between subordinate sessions, and 20 min of rest intervals were provided between primary experimental groups to ensure sufficient recovery and minimize carryover fatigue effects.

3. Results

This study adopted a within-subjects (repeated-measures) design, in which all 13 participants experienced all 12 lighting conditions. Normality of the data was assessed using the Shapiro–Wilk test, and homogeneity of variances was verified using Levene’s test. Only parameters that satisfied these preliminary assumptions were included in the subsequent statistical analysis. Given the repeated-measures experimental design, where all participants experienced all lighting conditions, repeated-measures ANOVA was employed to analyze the effects of blackboard reflectance, illumination ratio, and correlated color temperature on visual fatigue and performance outcomes. Post hoc pairwise comparisons were conducted using the least significant difference (LSD) method, which was chosen for its sensitivity in exploratory research. A significance level was set at 0.05 for all tests. Given the exploratory nature of this study and the limited sample size, results should be interpreted with caution and require validation in confirmatory studies.

3.1. Subjective Scale Analysis

The subjective scale data met the statistical assumptions described above. Differences in mean subjective visual fatigue scores were calculated under identical paperboard reflection coefficients. These comparisons were conducted both before and after the experiment under conditions of identical paperboard reflection coefficients, as well as between conditions with different reflection coefficients. A greater difference in scores indicated a higher accumulation of fatigue. As shown in Table 6, the LSD method was employed for post hoc multiple comparisons to identify significant differences in subjective fatigue scores among groups.

Table 6. Pairwise comparisons of subjective visual fatigue scores among paperboard types using the LSD method.

Paperboard Type	Mean of Subjective Visual Fatigue (I)	Paperboard Type	Mean of Subjective Visual Fatigue (I)	Subjective Visual Fatigue Mean Difference (I–J)	Significance	95% Confidence Interval	
						Lower Limit	Upper Limit
White Paperboard	1.0000	White Paperboard	2.3077	–1.30769 *	0.040	–2.5492	–0.0662
Green Paperboard	2.9231	Green Paperboard	1.0000	1.92308 *	0.003	0.6815	3.1646
Black Paperboard	2.3077	Black Paperboard	2.9231	–0.61538	0.321	–1.8569	0.6262

Note: * The significance level of the mean difference is 0.05.

Table 6 presents statistically significant differences in subjective visual fatigue between experimental conditions when employing paperboards with distinct reflectance coefficients as visual stimuli in the VDT environment. Specifically, significant differences were observed between the white and green paperboards ($p < 0.05$) and between the white and black paperboards ($p < 0.05$). In contrast, no statistically significant difference was observed between the green and black paperboards, likely attributable to the marginal differences in their reflection coefficients and color intensity.

To further analyze the impact of reflection coefficients, differences in subjective visual fatigue ratings before and after the experiment were assessed for each paperboard type. As depicted in Figure 4, the white paperboard exhibited the smallest incremental increase in subjective fatigue scores. When combined with the results of inter group analyses, the visual fatigue level induced by the white paperboard was significantly lower compared to the green and black paperboards. In contrast, the absence of statistical significance between the green and black paperboards prevented a definitive comparison of fatigue dynamics between these two experimental groups using conventional difference score methodologies.

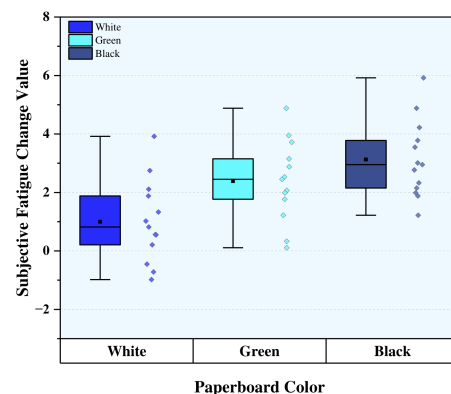


Figure 4. Subjective fatigue change values for different paperboard colors.

3.2. Eye Movement

Raw eye tracking data were processed using the Tobii I-VT Fixation Filter (Tobii AB, Stockholm, Sweden) to ensure accurate extraction of core oculomotor metrics. Visual fatigue was quantitatively assessed via six parameters: fixation frequency, total fixation duration, average fixation duration, number of saccades, average saccade amplitude, and average saccade peak velocity. Specifically, fixation frequency, total fixation duration, average fixation duration, and the number of saccades exhibited a positive correlation with visual fatigue, whereas average saccade amplitude and average saccade peak velocity demonstrated a negative correlation with visual fatigue [10,54].

Fixation-related parameters reflect the stability and efficiency of the visual information processing [45]. Increased fixation frequency and prolonged fixation duration typically indicate greater difficulty in extracting visual information, often associated with visual fatigue [45,50]. As fatigue accumulates, the visual system requires more frequent and longer fixations to process the same visual stimulus, reflecting reduced neural efficiency [55–57].

Saccade related parameters provide insight into oculomotor control and cognitive effort. An increased number of saccades may indicate heightened search activity or instability in gaze control, both of which are associated with visual fatigue [50,56]. In contrast, average saccade amplitude and average saccade peak velocity are inversely related to fatigue: as fatigue increases, saccade amplitude decreases and peak velocity slows, reflecting diminished oculomotor function and neural control efficiency [45,50,57]. Previous studies have consistently demonstrated that visual fatigue accumulation leads to reduced saccadic eye movements [57], while changes in saccade duration and amplitude serve as reliable indicators of fatigue state [56,57].

To ensure precise data processing, the Tobii Pro Lab software (version 1.194) was configured with the following parameters: the maximum gap length of 75 ms, the I-VT fixation classification threshold of 30°/s, and the minimum fixation duration of 60 ms. The Tobii I-VT Fixation filter, optimized for relatively stationary experimental settings, was selected as the most appropriate filtering method. Event marker points were defined as the start and end times of the two Landolt ring visual acuity tests conducted before and

after each experimental condition, thereby ensuring consistent temporal alignment for data analysis.

3.2.1. Results of Part 1 Experiment

The differences in fixation frequency and average saccade amplitude during Landolt ring visual acuity test successfully passed the basic statistical tests. Consequently, multiple comparisons were conducted based on the LSD method, as outlined in Section 3.1. The results revealed a statistically significant difference in fixation frequency between white and green paperboards, while no significant differences were observed between white and black paperboards or green and black paperboards. For the average saccade amplitude, a significant difference was found between white and black paperboards, whereas no significant differences were observed between white and green or green and black paperboards.

Further analysis of the eye movement parameter changes is presented in Figure 5a,b. The white paperboard condition exhibited the smallest mean increase in fixation frequency before and after the Landolt ring visual acuity test compared to the black and green paperboards. Given that fixation frequency demonstrated a positive correlation with visual fatigue, and statistically significant differences were observed only between white and green paperboards, these findings indicate significantly reduced visual fatigue when utilizing the white paperboard as the visual work surface background during VDT operations compared to the green paperboard. Similarly, the mean change in average saccade amplitude before and after Landolt ring visual acuity test was smallest for the white paperboard, indicating the smallest decrease in saccade amplitude under the white paperboard condition. A negative correlation was observed between average saccade amplitude and visual fatigue, suggesting that the use of white paperboard as the VDT background significantly reduced visual fatigue compared to black paperboard. Combining the results for fixation frequency and average saccade amplitude, it can be concluded that in environments where both the VDT and the surrounding visual background are used as working surfaces, white paperboard induces significantly lower levels of visual fatigue compared to either green or black paperboards. This suggests that a higher reflection coefficient of the visual background is associated with a smaller increase in fixation frequency, and a smaller decrease in average saccade amplitude, collectively contributing to a reduced accumulation of visual fatigue.

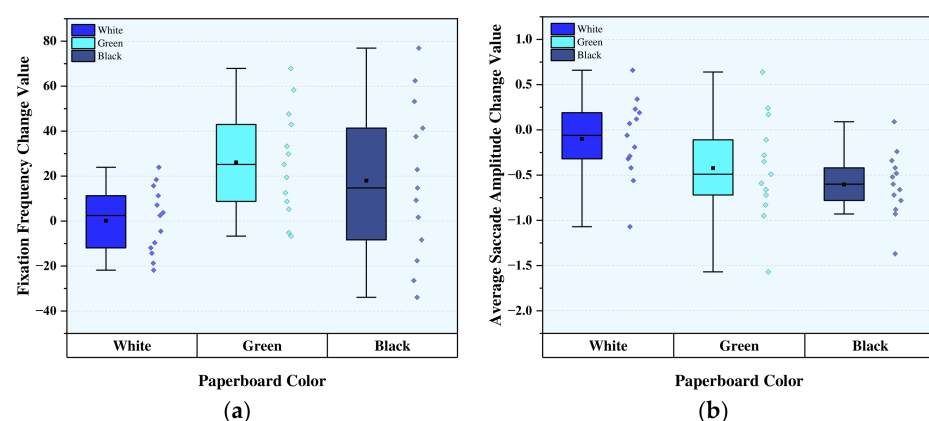


Figure 5. (a) Fixation Frequency change values for different paperboard colors in the Landolt ring visual acuity test. (b) Average Saccade Amplitude change values for different paperboard colors in the Landolt ring visual acuity test.

3.2.2. Results of Part 2 Experiment

- Under the same color temperature and different illumination ratios

The changes in fixation frequency during the Landolt ring visual acuity test satisfied the basic statistical assumptions, allowing for multiple comparisons between groups using the LSD method, as described in Section 3.1. The results demonstrated statistically significant differences ($p < 0.05$) between several illumination ratio conditions. Specifically, significant differences were observed between the following pairs: 300 lx:500 lx and 300 lx:750 lx, 300 lx:500 lx and 500 lx:750 lx, 500 lx:500 lx and 300 lx:750 lx, and 500 lx:500 lx and 500 lx:750 lx.

Further analysis of eye movement parameters (Figure 6) revealed that the mean change in fixation frequency under the illumination ratio of 300 lx:500 lx was significantly greater than that observed for the 300 lx:750 lx and 500 lx:750 lx ratios. Similarly, the illumination ratio of 500 lx:500 lx yielded a larger mean change in fixation frequencies compared to both the 300 lx:750 lx and 500 lx:750 lx conditions. A negative correlation was identified between the brightness of the blackboard and the degree of visual fatigue when VDT operations were conducted under identical color temperature and desktop illumination conditions. This finding indicates that increasing the blackboard's illumination level effectively mitigates visual fatigue. Conversely, when the blackboard's illumination was fixed, variations in desktop illumination did not exhibit a statistically significant effect on visual fatigue.

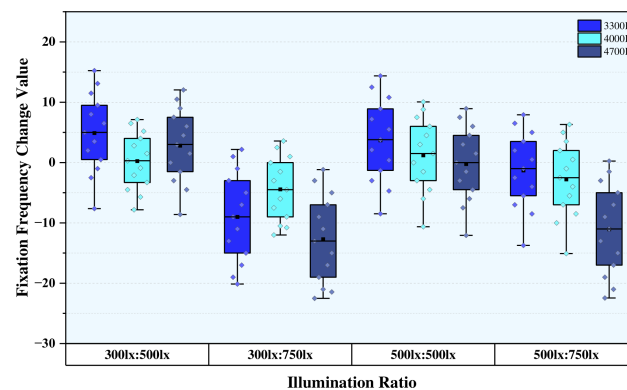


Figure 6. Fixation Frequency change values under varying illumination ratios during Landolt ring visual acuity test.

Among the evaluated conditions, the illumination ratios of 300 lx:750 lx and 500 lx:750 lx for the desktop and blackboard demonstrated the smallest impact on the accumulation of visual fatigue in students. Therefore, these illumination ratios are recommended as favorable configurations for VDT multimedia classrooms.

- Under the same illumination ratio and different color temperatures

Changes in the average saccade peak velocity, fixation frequency, and average fixation duration during the Landolt ring visual acuity test satisfied the basic statistical assumptions. This permitted subsequent multiple comparative analyses using the LSD method, as detailed in Section 3.1. The analysis revealed significant differences in fixation frequency and average fixation duration between 3300 K and 4000 K ($p < 0.05$), and in average saccade peak velocity between 3300 K and 4000 K ($p < 0.05$), as well as between 4000 K and 4700 K conditions ($p < 0.05$). Figure 7a,b present the changes in eye movement parameters. The mean differences in fixation frequency and average fixation duration, calculated before and after the Landolt ring visual acuity test, indicate that as the CCT increased from 3300 K to 4000 K, fixation frequency changes decreased, whereas average fixation duration changes increased. Given the negative correlation between fixation frequency changes and visual fatigue, and the positive correlation between average fixation duration changes and visual fatigue, it can be inferred that the degree of visual fatigue was reduced at 4000 K compared to 3300 K.

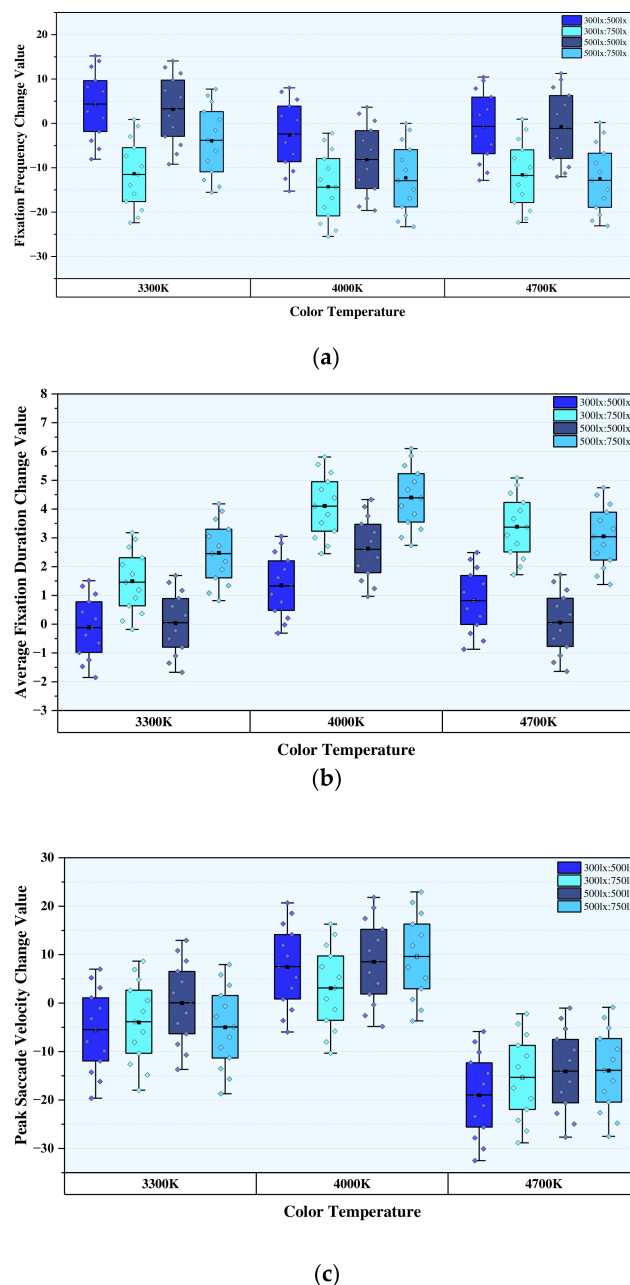


Figure 7. (a) Fixation Frequency change values under varying color temperatures during Landolt ring visual acuity test. (b) Average Fixation Duration change values under varying color temperatures during Landolt ring visual acuity test. (c) Peak Saccade Velocity change values under varying color temperatures during Landolt ring visual acuity test.

As illustrated in Figure 7c, elevating the CCT from 3300 K to 4000 K increased the average peak velocity, whereas a further rise to 4700 K reduced it. Since average saccade peak velocity is inversely correlated with visual fatigue, these findings suggest that visual fatigue was lower under the 4000 K lighting condition and higher at both 3300 K and 4700 K.

3.3. Index of Mental Capability

Visual fatigue reduces visual performance and, consequently, reduces working efficiency [58]. As a result, the IMC, a measure of working efficiency, is an important metric for evaluating visual fatigue. A decline in IMC corresponds to increased mental fatigue, whereas an improvement in IMC indicates enhanced working efficiency [10,59].

The IMC was adapted from previous studies on mental workload assessment [59–61]. The original formula for proofreading tasks is:

$$\text{IMC} = (\text{Number of characters read}/2) \times [(\text{Target deletions} - \text{Erroneous deletions})/\text{Target deletions}] \quad (1)$$

For the Landolt ring visual acuity test in this study, we adapted the formula as follows:

$$\text{IMC} = (\text{Number of rings presented}/2) \times [(\text{Total target orientations} - \text{Incorrect responses})/\text{Total target orientations}] \quad (2)$$

Worked example: If a participant was presented with 50 Landolt rings, with 40 target orientations requiring identification, and made 5 incorrect responses, the IMC would be:

$$\text{IMC} = (50/2) \times [(40 - 5)/40] = 25 \times (35/40) = 25 \times 0.875 = 21.875 \quad (3)$$

Higher IMC values indicate greater working efficiency. It should be noted that the IMC was originally developed for proofreading tasks and has not been widely validated for Landolt ring tasks. This represents a limitation of the current study.

3.3.1. Results of Part 1 Experiment

The IMC results from the Landolt ring visual acuity test and the Anfimov's Chart Task passed the basic statistical checks. Multiple independent group comparisons, based on the LSD method, were performed as outlined in Section 3.1. For the IMC of Landolt ring visual acuity test, significant differences were found among the groups using white, green, and black paperboards ($p < 0.05$). For the Anfimov's Chart Task, significant differences in IMC were observed only between white and black paperboards, with no significant differences emerging between white and green or green and black paperboards.

Further analysis of the IMC changes is shown in the comparison plots. As depicted in Figure 8a, the mean IMC of Landolt ring visual acuity test was highest under the white paperboard condition, compared to the black and green paperboards. This suggests that when both the VDT and its surrounding environment serve as visual work surfaces, higher background reflection coefficients lead to higher IMC values and improved working efficiency.

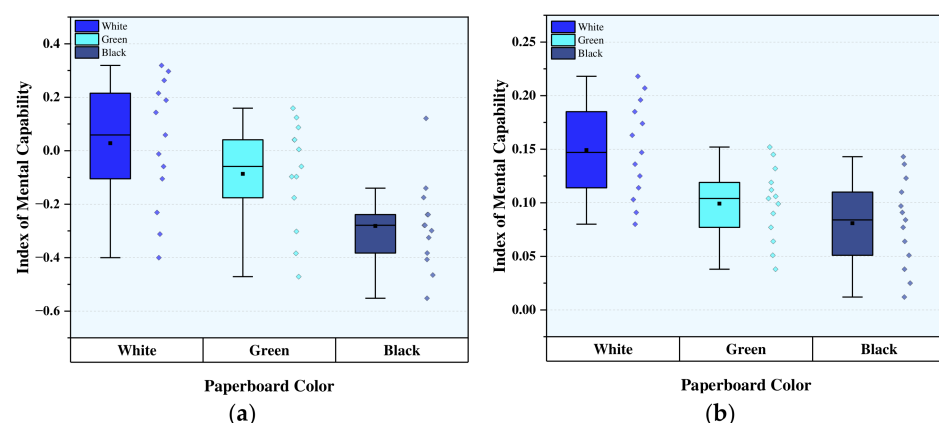


Figure 8. (a) Index of mental capability for Landolt ring visual acuity test. (b) Index of mental capability for the Anfimov's Chart Task.

Similarly, Figure 8b shows that the mean IMC of the Anfimov's Chart Task was higher with the white paperboard condition than with the black and green paperboards. Analysis revealed significant IMC differences only between white and black paperboard conditions, indicating that working efficiency was significantly enhanced under white paperboard conditions compared to black paperboard conditions.

3.3.2. Results of Part 2 Experiment

- Under the same color temperature and different illumination ratios

The IMC of Landolt ring visual acuity test passed the basic statistical tests. Multiple group comparisons based on the LSD method were conducted as described in Section 3.1. The results showed highly significant differences between 300 lx:750 lx and 500 lx:500 lx ($p < 0.001$), as well as significant differences between 300 lx:500 lx and 300 lx:750 lx ($p < 0.05$), 300 lx:500 lx and 500 lx:750 lx ($p < 0.05$), and 500 lx:500 lx and 500 lx:750 lx ($p < 0.05$).

Figure 9 compares the IMC changes for Landolt ring visual acuity test before and after the experiment under different illumination ratios. The findings suggest that, under constant color temperature and desktop illumination, elevating the blackboard's illumination level mitigated the decline in IMC, thereby reducing working efficiency loss within a specific range. However, when the blackboard's illumination level remained constant, changes in desktop illumination had no significant effect on working efficiency.

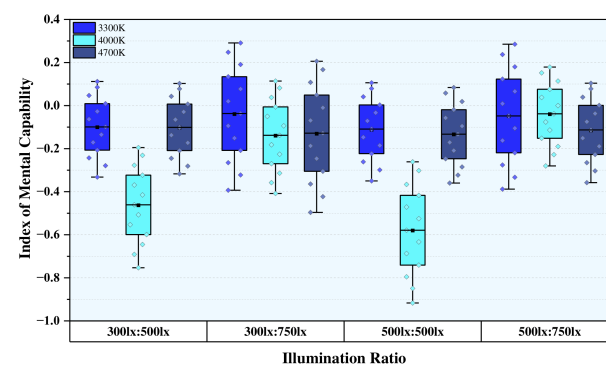


Figure 9. Index of mental capability for Landolt ring visual acuity test under different illumination ratios.

- Under the same illumination ratio and different color temperatures

The IMC values from Landolt ring visual acuity test and the Anfimov's Chart Task passed the basic statistical tests. Multiple group comparisons using the LSD method were conducted as outlined in Section 3.1. Significant differences in IMC values for Landolt ring visual acuity test were found between 4000 K vs. 4700 K ($p < 0.05$), 3300 K vs. 4700 K ($p < 0.05$), and 3300 K vs. 4000 K ($p < 0.05$).

Figure 10a,b illustrate the changes in IMC across different color temperatures. For Landolt ring visual acuity test, the mean IMC was highest at 4700 K, intermediate at 3300 K, and lowest at 4000 K. Similarly, for the Anfimov's Chart Task, the mean IMC was greater at 4700 K than at 4000 K or 3300 K. These results suggest that a CCT of 4700 K results in the highest working efficiency and the smallest reduction in efficiency.

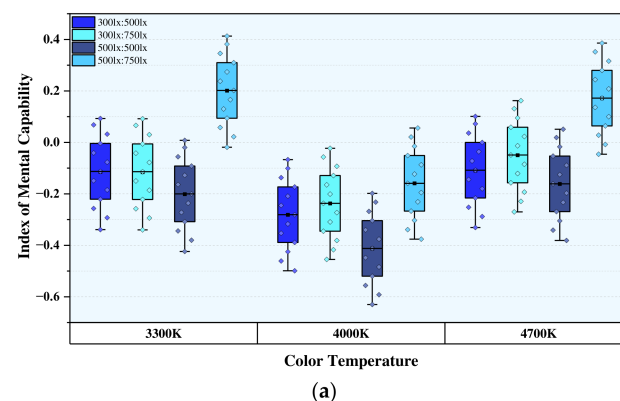


Figure 10. Cont.

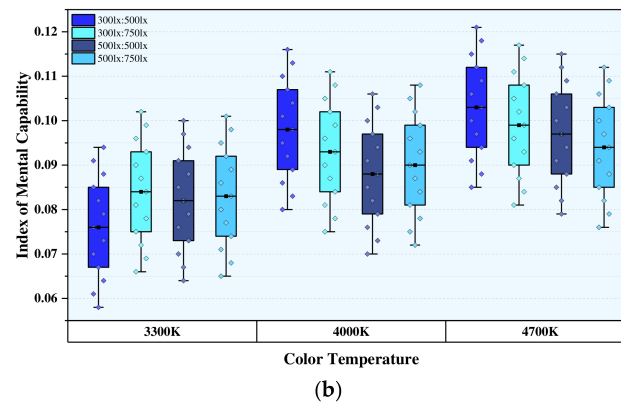


Figure 10. (a) Index of mental capability for Landolt ring visual acuity test under different color temperatures. (b) Index of mental capability for the Anfimov's Chart Task under different color temperatures.

4. Discussion

4.1. Main Findings

This study investigated the effects of blackboard reflection coefficients, illumination ratios, and correlated color temperature on students' visual fatigue and efficiency in multi-media classrooms. Experiment 1 demonstrated that higher blackboard reflection coefficients significantly reduced visual fatigue and enhanced efficiency. Experiment 2 revealed the dynamic influence of the ratio of desktop illumination to blackboard illumination, as well as CCT, on fatigue and efficiency. Results showed that increasing blackboard illumination effectively mitigated fatigue under constant CCT, while desktop illumination had no significant impact when blackboard illumination was fixed. Efficiency peaked at 4700 K, while visual fatigue was minimized at 4000 K. Overall, these findings highlight the intricate interplay among reflection coefficients, illumination ratios, and CCT, and demonstrate their joint influence on visual comfort and learning outcomes.

4.2. Interrelation Between Experiments

Experiment 1 established the fundamental role of blackboard reflection coefficients in reducing visual fatigue. Experiment 2 further demonstrated that the ratio of desktop illumination to blackboard illumination and CCT dynamically influence fatigue and efficiency. These findings suggest that while reflection coefficients serve as a foundational determinant of visual comfort, illumination ratios and CCT provide refined control over fatigue and efficiency in dynamic classroom settings.

4.3. Further Analysis: Exploratory Analysis of Age Effects and Physiological Mechanisms Underlying CCT Responses

The results suggest that participants of different age groups may exhibit significant variations in fatigue and efficiency. For example, younger individuals might be more sensitive to lighting conditions, while older participants may have different fatigue thresholds [62–64]. Future research should stratify participants by age to validate these hypotheses.

Moreover, the observed efficiency variations across CCT values may reflect underlying physiological mechanisms. The highest efficiency among the tested CCT values at 4700 K might reflect a balance between visual comfort and cognitive alertness, whereas lower or higher CCTs might induce visual fatigue or disrupt circadian rhythms. Specifically, higher CCT is known to suppress melatonin secretion, enhancing alertness and cognitive performance in the short term, but prolonged exposure may contribute to visual fatigue and circadian disruption [64–67]. Conversely, lower CCT has a milder impact on melatonin

and may be more comfortable for extended viewing, which aligns with our finding that visual fatigue was minimized at 4000 K.

This dissociation between the CCT for efficiency (4700 K) and that for fatigue reduction (4000 K) presents a design tension. For lighting designers, a practical solution may involve tunable lighting systems that adjust CCT according to time of day and task demands: higher CCT (e.g., 4700–5000 K) during morning hours when alertness is needed for learning, transitioning to lower CCT (e.g., 4000 K) during prolonged afternoon study sessions to minimize fatigue. Future research incorporating physiological metrics such as melatonin levels, pupillary response, and subjective alertness would help elucidate these mechanisms and validate such dynamic lighting strategies.

4.4. Strengths

This study provides practical strategies for optimizing multimedia classroom lighting to safeguard students' vision, reduce visual fatigue, and improve learning efficiency. The findings emphasize the critical role of lighting configurations in enhancing visual comfort and supporting multimedia-assisted instruction.

4.5. Limitations and Future Directions

4.5.1. Sample Size and Statistical Considerations

Several statistical limitations should be acknowledged. First, the sample size ($n = 13$) is relatively small, which limits statistical power and may reduce the generalizability of the findings. Recruitment of adolescent participants with strict inclusion criteria, including normal color vision, no refractive errors, no history of eye diseases, posed practical challenges, resulting in this modest sample size. The age range of 12–18 years spans a developmental period during which ocular and cognitive functions may change. Exploratory subgroup analysis (12–14 vs. 15–18) showed similar trends, but the small sample size prevented robust statistical conclusions. Future studies should use narrower age bands or larger cohorts to examine age-related differences in lighting-induced visual fatigue. It should also be noted that while participants with myopia were included (provided their corrected visual acuity reached 5.0), the high prevalence of myopia among Chinese adolescents [68] represents an important contextual factor that may influence the generalizability of the findings.

Second, no *a priori* power analysis was conducted due to the lack of preliminary data on effect sizes in this specific research context. This study therefore serves as an exploratory investigation intended to generate hypotheses and provide effect size estimates for future confirmatory research.

Third, the experimental design involved multiple comparisons across 12 lighting conditions. The LSD method used for post hoc comparisons does not control for the increased risk of Type I error associated with multiple testing. We chose not to apply a conservative correction such as Bonferroni because, in this small sample exploratory study, such an adjustment would substantially increase Type II error, potentially obscuring meaningful patterns worthy of future investigation. Given the exploratory nature of this research, we prioritized sensitivity to detect potential effects, with the understanding that findings require validation in larger confirmatory studies.

Future studies should employ larger and more diverse samples and include *a priori* power calculations to ensure adequate statistical power. Confirmatory studies with prespecified hypotheses and appropriate corrections for multiple comparisons, such as Bonferroni or false discovery rate, are needed to validate the findings reported here. Additionally, replication in real classroom settings with larger participant cohorts would enhance the external validity of the results.

Moreover, the present sample included only 5 male and 8 female participants, which precluded any meaningful gender-based analysis. Future research should recruit larger and more balanced male female cohorts. Regarding age, the range of 12 to 18 years spans a developmental period during which ocular and cognitive functions may change. We suggest that future studies use narrower age bands, for example 12 to 14 years and 15 to 18 years. This division roughly corresponds to pubertal stages that may affect visual processing. Our exploratory subgroup analysis comparing these two age groups showed similar trends, but the small sample size prevented robust statistical conclusions. Larger cohorts with these stratified age groups will help clarify age related differences in lighting induced visual fatigue.

4.5.2. Reflection Coefficient Range

Although a reflection coefficient of 0.61 effectively reduced fatigue and improved efficiency, the effective range boundaries remain to be determined, and further research is needed to establish thresholds. Further exploration is needed to establish both the minimum and maximum effective thresholds for this parameter.

4.5.3. Illumination and CCT Settings

The limited number of illumination and CCT values, along with wide intervals, may have reduced the precision of the findings. Future research should use narrower parameter ranges to enable a more granular analysis.

Moreover, the interaction between CCT and illuminance (Kruithof diagram) was not systematically examined in this study, as we varied both parameters but did not fully cross all combinations. Our findings on CCT effects are therefore limited to the tested illuminance levels (300 lx and 500 lx). Future research should systematically vary both CCT and illuminance to map the comfort zone for multimedia classrooms [40].

4.5.4. Environmental Conditions

This is an important limitation because real classrooms always contain natural daylight, which was absent in our setup.

First, the experiments were conducted in a fully dark laboratory to eliminate external interference. This controlled approach was necessary to isolate the effects of the targeted lighting parameters (reflectance, illumination ratio, and CCT) without confounding influences from variable daylight conditions. However, this means that natural daylight was completely absent from our setup, which is an important limitation because real classrooms always have daylight. In real world multimedia classrooms often incorporate natural daylight, which can introduce glare, diminish blackboard legibility, and compromise lighting uniformity. We acknowledge that this tradeoff between internal validity and ecological realism limits the direct generalizability of the findings. Therefore, the results should be interpreted as identifying trends under controlled conditions, and future studies should incorporate both natural and artificial light conditions to develop more comprehensive lighting optimization strategies that validate and extend these findings.

Second, the experimental design did not fully isolate the effects of blackboard reflectance from contrast polarity. While the white and green paperboards allowed for comparison of reflectance under constant positive polarity, the black paperboard condition introduced both reduced reflectance and reversed contrast polarity. However, it is important to note that this confounding reflects the reality of classroom environments, where different types of blackboards naturally vary along both dimensions simultaneously. Moreover, based on psychophysical evidence that contrast polarity is not a primary factor in Landolt C orientation discrimination tasks [69,70], we believe the findings remain interpretable. Future studies should systematically manipulate reflectance while holding

contrast polarity constant, and vice versa, to fully disentangle these factors and further validate the current findings.

Third, the chromatic disparity between the Dell monitor (8835 K) and ambient LED lighting (4000 K) in this experiment was intentional, reflecting real world multimedia classroom conditions where electronic whiteboards and general lighting fixtures often have different CCTs. This setup enhances ecological validity by replicating the mixed-lighting environments students actually experience. While the display CCT was held constant to isolate the effects of ambient lighting variations, we acknowledge that display-ambient interactions may influence visual fatigue. Future research should systematically vary both display and ambient CCTs to investigate their combined effects and optimize lighting design for multimedia classrooms.

Additionally, the reduced viewing distance of 0.8 m in our simulated environment changes accommodation and convergence demands compared to the 4.8 m distance in a real classroom, which may influence visual fatigue. This limitation should be considered when extrapolating our findings to full-scale educational settings.

4.5.5. Flicker Consideration

Flicker from artificial lighting is a known cause of visual fatigue, especially when LED fixtures and screens are used together in multimedia classrooms. Many low-cost lighting products on the market have serious flicker problems. They can cause eye strain, headaches, and make it harder to focus on tasks. We checked our LED fixtures and confirmed they are flicker free according to IEEE 1789-2015 [52], but this is not always true in real classrooms. Therefore, we suggest that schools should choose certified flicker free lights, even at lower prices. Making more people aware of this issue might push manufacturers to produce safe and affordable flicker free lighting. That would directly help protect students' vision.

4.5.6. Practical Recommendations for Classroom Lighting

Despite the exploratory nature of this study, our findings offer a few qualitative directions for lighting design in multimedia classrooms. Using blackboard surfaces with higher reflectance, such as light-colored boards, appears to improve luminance contrast and may help reduce visual fatigue. Keeping the blackboard noticeably brighter than the desk also seems beneficial. For color temperature, tunable LED fixtures could be considered: a higher CCT in the morning to support alertness, and a lower CCT in the afternoon to minimize fatigue during prolonged work. These suggestions come from a controlled laboratory study and should be tested in real classrooms with natural daylight before wide adoption.

5. Conclusions

This exploratory study examined the influence of multimedia classroom lighting on secondary school students' visual fatigue through simulated learning experiments in a VDT environment. Two experiments were conducted: the first assessed the effect of blackboard reflection coefficients, and the second evaluated various lighting conditions, including illumination ratios and correlated color temperatures. Subjective visual fatigue data, EMP, and IMC were employed to assess visual fatigue and working efficiency under these differing conditions.

The results suggest that higher blackboard reflection coefficients effectively reduce visual fatigue and enhance work efficiency. Under constant color temperature and uniform desktop illumination, increasing blackboard illumination mitigates visual fatigue and minimizes efficiency decline. Conversely, changes in desktop illumination had no significant impact when blackboard illumination was held constant. Furthermore, when the

illumination ratio was fixed, a color temperature of 4700 K achieved the highest working efficiency, whereas 4000 K exhibited the least increase in visual fatigue. These findings provide preliminary practical guidance for reducing visual fatigue and enhancing work efficiency within the lighting environment of secondary school multimedia classrooms.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16112272/s1>, Table S1: VFS-10 (Visual Fatigue Scale); Table S2: Landolt C checklist; Figure S1: The Triple-Surface Anfimov Task.

Author Contributions: All authors contributed to the study conception and design. Material preparation, experimental work, data collection and analysis were performed by W.B., J.W., X.C. (Xianyun Cai), X.C. (Xin Cao) and X.Z. The first draft of the manuscript was written by W.B. and all authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Medical Ethics Committee of Chongqing People’s Hospital (approval number: IIT S2026-042-01; date of approval: 12 May 2026).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are not publicly available due to ethical and legal restrictions involving minors in accordance with Chinese data protection laws.

Conflicts of Interest: Author Xiao Zhang is currently employed by China Construction First Group. The present research was conducted partly during her academic study and partly on her personal time after joining the company, without any involvement or funding from the company. The remaining authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

VDT	Visual Display Terminal
CCT	Correlated Color Temperature
IMC	Index of Mental Capacity
VFS-10	Visual Fatigue Scale
CQS	Color Quality Scale

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