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Study on the Effects of Display Color Mode and Luminance Contrast on Visual Fatigue

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ABSTRACT Using electronic devices at night can easily cause visual fatigue. We investigated the conjoint effects of color mode and luminance contrast on visual fatigue and subjective preference when using electronic devices under low screen luminance and low ambient illumination at night. A multidimensional approach based on eye and subjective measures was used to test 2 color modes (dark mode, light mode) and 6 luminance contrast ratios (0.969, 0.935, 0.868, 0.855, 0.725, 0.469) in a 2 × 6 experimental design. We used eye movement tracking technology to collect blink rate and pupil diameters, and used the Likert scale to measure subjective visual fatigue scale and preference. Results showed that reading in the dark mode reduced visual fatigue, as reflected by an increase in blink rate and pupil accommodation. Lower subjective visual fatigue scale and higher preference were found in the light mode due to subjects' using habits of dark texts on a light background. There was a significant negative correlation between (text-background) luminance contrast and visual fatigue, and subjects preferred higher luminance contrast. We observed the lowest visual fatigue under the luminance contrast of 0.969 in the dark mode, and the lowest subjective preference when the luminance contrast was lower than 0.725. We suggest the users should choose the dark mode to reduce visual fatigue when using electronic devices at night. These findings also provide a reference for the design of interactive interfaces such as tablets and mobile phones, and have practical implications for reducing visual fatigue.

INDEX TERMS Eye tracking, electronic devices, color mode, luminance contrast, visual fatigue.

I. INTRODUCTION

With the advent of the information age, daily work and study are inseparable from electronic devices. Computers, mobile phones, tablets and other electronic devices play an irreplaceable role in our work and life. Long-time use of electronic screens can cause eyestrain. In modern life, people are accustomed to looking at the electronic screen for a long time after turning off lights at night. Looking at electronic screens for a long time in a dark environment may cause serious damage to the eyeball surface and the macular area, and induce dry eye, glaucoma, conjunctivitis, myopia and other diseases. It could even cause blockage of the retinal arteries and blood vessels, and the visual acuity will decrease in a short time. If the retina is completely blocked, there will be short-term blindness symptoms, commonly known as ''ocular stroke'' [1]–[3]. The traditional eye protection mode reduces visual fatigue by reducing the color temperature to reduce the damage caused by blue light to the retina [4] and reducing screen brightness [5]. The dark mode is a new display color mode. Presenting dark texts on a light background, such as presenting black texts on a white background, is the light mode, also known as positive polarity. Presenting light texts on a dark background, such as presenting white texts on a black background, is the dark mode, also known as negative polarity [6]. The dark mode has three advantages: saving power, reducing visual fatigue (especially when working at night or in a dim environment) and enhancing interface aesthetics [7]. However, users have different opinions about the dark mode. Sanders suggested that positive polarity (light background) might reduce the visibility of reflected light, so it was more conductive to viewing in the case of glare or reflection problems [8]. Buchner *et al.*. found that positive polarity resulted in better visual performance [9], [10]. Shieh *et al.*. investigated the influence of reflection and polarity on viewing distance and subjective visual fatigue. Results showed when there was no reflection, the viewing distance of negative polarity was significantly longer than that of positive polarity, and a longer viewing distance meant lower visual fatigue [11]. Ericson *et al.* found that the dark mode was more conductive

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TABLE 1. CIE and RGB coordinate value of the colors used in the dark mode.

Color	(R, G, B)	Luminance (cd/m^2)	x	y
Background 1(B_1)	(26, 26, 26)	0.40	0.2970	0.3120
Background 2(B_2)	(89, 89, 89)	1.90	0.3025	0.3197
Text 1(T_1)	(242, 242, 242)	25.60	0.3025	0.3206
Text 2(T_2)	(191, 191, 191)	11.90	0.3025	0.3204
Text 3(T_3)	(140, 140, 140)	5.25	0.3026	0.3200

to reducing visual fatigue when using electronic screens in a dark environment [12], [13]. Wang *et al.* found no significant difference in the effects of positive and negative polarity on visual fatigue [14]. However, these studies haven't reached a consensus on which display color mode is more conductive to reducing visual fatigue. Another important factor for screen display is luminance contrast. Screen luminance contrast is an indicator to measure the brightness difference between the viewing target and its adjacent background in the field of view of the display. Ling *et al.* found that high luminance contrast might improve visual performance [15]–[17]. Wang found that visual performance improved as luminance contrast increased to 8:1 and then decreased once luminance contrast was higher than 8:1 [14]. Shieh found that better performance was showed under the contrast ratio 1:3 than 1:15 [18]. Ou and Sun found an interaction between polarity and luminance contrast. In a light background, visual comfort increased with increasing luminance contrast. In a dark background, the highest visual comfort value can be achieved with moderate luminance contrast [19]. However, most of the existing work on the visual fatigue of the display were carried out under normal office lighting and normal screen brightness. Relatively few studies thoroughly simulated the night environment (including low ambient illuminance and low screen brightness) to study the visual fatigue caused by looking at the display at night. And these studies have adopted subjective tasks and questionnaires to study visual fatigue, which has a limitation.

In our study, we used both light mode and dark mode. Luminance contrast is influenced by the screen luminance and the text-background color brightness difference. In order to study the impact of text-background color luminance contrast on visual fatigue, this study controlled the screen luminance to 28cd/m^2 (5% screen brightness, users generally use low screen brightness when using electronic devices at night). Luminance contrast is defined as the ratio between the difference of text-background luminance and the sum of text-background luminance (Michelson contrast) [20]. Environmental illumination is an important factor affecting visual performance. In order to study the night eye protection mode, we controlled the ambient illumination to less than 3lux. This study aims to solve the following problems: when using electronic devices under low screen luminance at night, how the color mode affects visual fatigue, how text-background luminance contrast affects visual fatigue and the interaction between color mode and luminance contrast. We used eye tracker to collect pupil signals and blink rate to detect visual fatigue, and used the Likert Scale to collect visual fatigue scale and subjective preference score. In the rest of the paper, the second part introduces the details of the experiment, the third part introduces the experimental data analysis, the fourth part discusses the data results, and the fifth part is the conclusion and application.

II. METHODS

A. EXPERIMENTAL DESIGN

This study evaluated two independent variables: color mode and (text-background) luminance contrast. The two considered display color mode conditions were light mode (dark texts on a light background, i.e., L.M.) and dark mode (light texts on a dark background, i.e., D.M.). As to (text-background) luminance contrast, we did not use too high or too low luminance contrast for more obvious experimental effect, but chose the luminance contrast commonly used in the dark mode design by existing systems, software, readers. Ambient illumination was less than 3lux and screen luminance was 28cd /m^2 (5% screen brightness). In the dark mode, there were two background colors with CIE values (x, y, L) of (0.2970, 0.3120, 0.40), (0.3025, 0.3197.1.90) and three text colors with CIE values of (0.3025, 0.3206, 25.60), (0.3025, 0.3204, 11.90), (0.3026, 0.3200, 5.25). Relevant data is shown in Table 1. Through the text-background color combinations of different brightness, a total of $2 \times 3 = 6$ luminance contrast ratios were obtained. In the light mode, keep the luminance contrast ratio the same and convert the background color to the text color. The text-background color combinations and luminance contrast used in the experiment are shown in Table 2.

TABLE 2. Luminance contrast used in the experiment.

Text-background color combination	Michelson contrast
experiment1 (B_1, T_1)	0.969
experiment2 (B_1, T_2)	0.935
experiment3 (B_2, T_1)	0.868
experiment4 (B_1, T_3)	0.855
experiment5 (B_2, T_2)	0.725
experiment6 (B_2, T_3)	0.469

We used both within-subject and between-subjects experiment design. We recruited 60 subjects and 10 subjects were randomly assigned to each of the 6 levels of luminance contrast, which was a between-subjects factor. Each subject completed two experiments of the color mode (light mode and dark mode under the same luminance contrast), which was a within-subject factor. In order to control the ambient illumination, we prepared a separate room surrounded by black curtains, and the experiment was conducted from 18:00 to 23:00. The whole experiment period was about 25 days. Illustrations of the different experimental conditions are shown in Fig. 1. The experimental environmental condition is shown in Fig. 2.

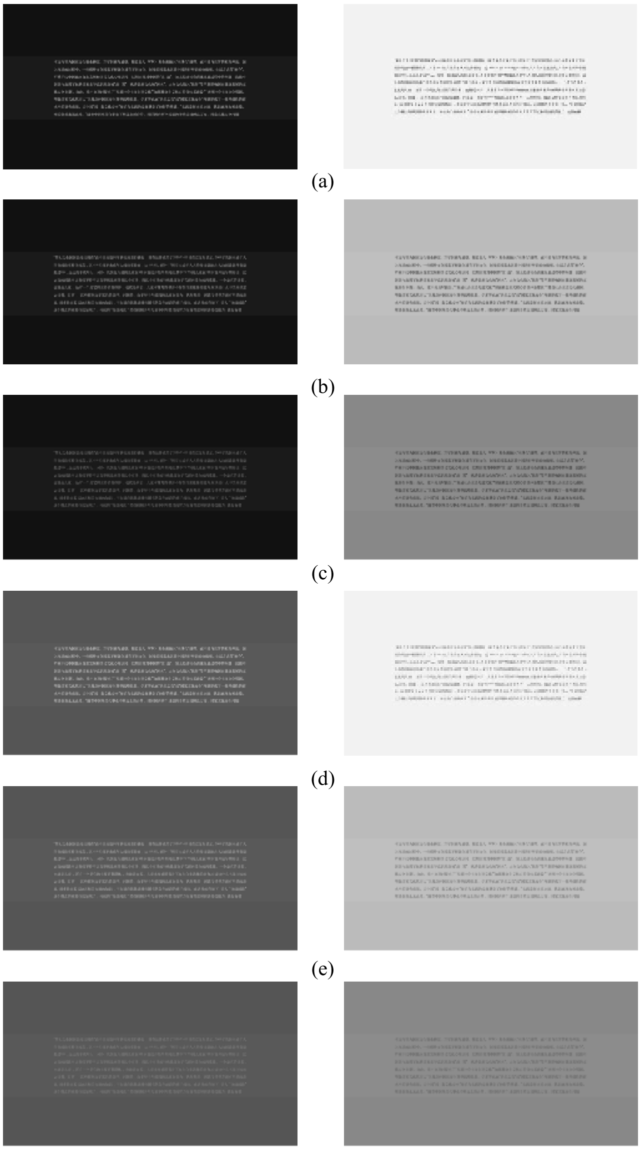

FIGURE 1. Illustrations of the different experimental conditions. The left column shows the dark mode stimuli, the right column shows the light mode stimuli. From top to bottom, the rows show the different luminance contrast: (a) 0.969, (b) 0.935, (c) 0.855, (d) 0.868, (e) 0.725, (f) 0.469.

B. SUBJECTS

In this study, 60 graduate students (35 male and 25 female) were recruited from Shandong University. Ages ranged from 22 to 30 years (M = 25, SD = 3), and all were right-handed. All subjects had a normal or corrected vision of 1.0 or above. Participants were not allowed to wear soft contact lenses and did not have any eye problems (such as color blindness, astigmatism *et al.*) or psychological problems. We investigated how often participants used the dark mode before the experiment. Among them, 8 participants used the dark mode frequently, 15 participants used it occasionally, and the remaining participants hardly used the dark mode. Subjects were asked to ensure good sleep and rest within 24 hours before the experiment.

FIGURE 2. Photo of a participant in the study.

C. APPARATUS

Benq 27-inch backlit LED display (SW271) was used in the experiment with an aspect ratio of 16:9, a resolution of 3840 × 2160, and a refresh rate of 60Hz. We used Minolta display color analyzer CA-310 to measure the luminance of the screen and text-background color CIE chromaticity value, and used Tobii-X2-30 eye tracker to record the pupil data and blink rate during the experiment. The resolution of the eye tracker is 1080 × 1024, the sampling frequency is 30Hz, the sampling accuracy is 0.5 degrees, and the allowed head motion range is 44cm × 22cm × 30cm. During the experiment, the subjects did not need to wear any equipment, and the eye tracker was placed under the computer screen to be hidden, which greatly reduced the interference to the subjects.

D. CONDITIONS OF THE WORKPLACE

Fig. 3 shows the specific parameters of the workplace. A monitor with a visor was placed on a 110cm-high table. The height of the chair was 73cm. The height of the monitor can be adjusted from 50cm to 61cm. The horizontal distance between the edge of the table and the center of the screen was 30cm. The inclination of the monitor was 105 degrees. The height of the monitor was adjusted according to the height of the subject, so that the viewing angle was 15 degrees. The horizontal distance between the subjects' eyes and the center of the screen was about 50cm.

E. TASK AND PROCEDURE

Similar to Gowrisankaran *et al.* 's study [21], [22] on visual fatigue, participants were asked to perform a reading task. We selected two popular science papers of similar difficulty as experimental materials. Each reading material was about 8, 400 words and presented on 21 pages, about 400 words per page. The reading time of each page was set to 1min. The characters were presented in Chinese characters with 20-pound Song Ti and 1.5-times the line spacing. The experiment process was as follows. The subjects entered the laboratory and firstly relaxed their eyes for 5 minutes to get a good visual state. After the relaxation, we explained the experiment process to the subjects and ensured that the subjects fully understood the task. Then the formal experiment began.

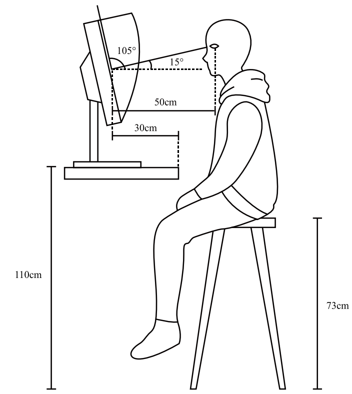

FIGURE 3. **The arrangement of the workplace in the experiment.**

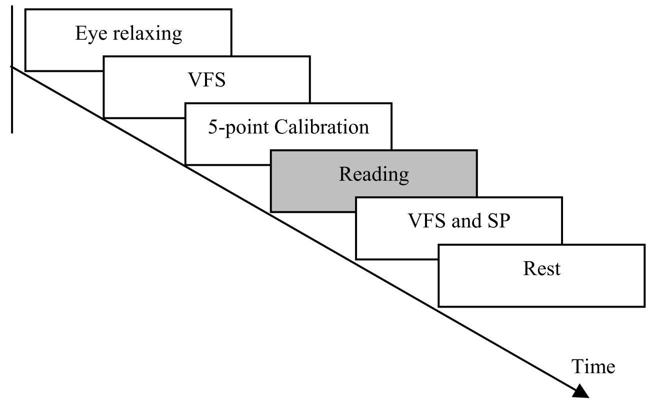

FIGURE 4. **Experimental process.**

Participants first filled out the subjective visual fatigue scale (i.e., VFS) and subjects who were too tired were excluded. Then turn off all the laboratory lights. The subjects sat in front of the monitor and adjusted the sitting position, about 50cm away from the monitor. Next, subjects performed a 5-point calibration, and started reading after the calibration was passed. During the reading process, subjects were asked to perform searching target words and reading comprehension to ensure a high concentration. After reading, the subjects reported their visual fatigue scale and subjective preference (i.e., SP) scores orally, which we recorded. After completing the first task, subjects rested for 10 minutes and performed the second reading task of the other color mode under the same luminance contrast. The procedure was the same as the first experiment process. After the experiment, we paid 60RMB to each participant. Each subject was required to read for 2 × 21min and the whole experiment process was about 60min. The experimental process is shown in Fig. 4.

F. DEPENDENT VARIABLES

We collected both objective and subjective indicators as dependent variables: blink rate, pupil accommodation, visual fatigue scale, and subjective preference.

The rapid closing and reopening of the eyelids are eye blinks. Blink rate (BR) is a well-known indicator of visual fatigue [23]–[26]. Studies have shown that when using a backlit video display terminal for work, the blink rate will be significantly reduced, especially in a dim light environment at night [24], [27]. A decrease in the blink rate can result in poor tear film quality and increases corneal exposure time, resulting in dry eyes. Studies have shown that dry eyes are an important cause of visual fatigue [2], [3]. So, a lower blink rate means greater visual fatigue when using electronic devices. In this study, blink rate was defined as the total number of blinks per reading task divided by the total reading time (in seconds).

The pupil accommodation (PA) can be used to measure eyestrain, which has a strong correlation with the degree of visual fatigue. Slower pupil accommodation means greater visual fatigue and vice versa [28]–[30]. We used linear regression to calculate the fluctuation of pupil diameter over time. The method was as follows. Firstly, divide the experimental data into 21 periods, each of which was 1min, and then calculate the average pupil diameter per minute respectively. Next perform linearly regression on the 21 average pupil diameters over time, and the regression coefficient obtained represented the pupil accommodation [5], [30].

The visual fatigue scale (VFS) adopted the questionnaire developed by Heuer and Hollendiek [31] which has been widely used in the subjective test of visual fatigue. The questionnaire includes the following six items: 1. It is hard for me to see. 2. I have a strange feeling around my eyes. 3. My eyes feel tired. 4. I feel numb. 5. I feel dizzy looking at the screen. 6. I have a headache. In the study, each question was rated on a scale of 10, with 1 meaning "not at all" and 10 meaning "very serious." The sum of the scores of the six items was considered as the final visual fatigue score. The visual fatigue scale was administered before and after each reading session.

We used the 7-point Likert scale to measure subjective preference (SP) [32]. 1 means "dislike it very much" and 7 means "like it very much".

III. RESULTS

The significance level was set at 0.05 for all statistical analyses. A two-way multivariate analysis of variance (MANOVA) was implied to examine the effects of two independent variables. Univariate results were also provided for each independent variable. The effect size was calculated. Duncan multiple paired-comparisons were used to examine the source of any significant effects. We performed a simple effect analysis when two variables showed a significant interaction. Pearson correlation analysis was performed on the correlation of four dependent variables. Means and standard deviations of BR, PA, VFS, and SP for each dependent variable are reported in Table 3.

The data analysis results of blink rate, pupil accommodation, visual fatigue scale, and subjective preference are respectively reported below. In each of the following parts, we elaborated on MANOVA, Duncan multiple paired-comparisons, and the interaction results of the four dependent variables.

A. BLINK RATE

The results of MANOVA showed that both the color mode [$F(1, 118) = 6.208$, $P < 0.05$. $\eta^2 = 0.054$] and

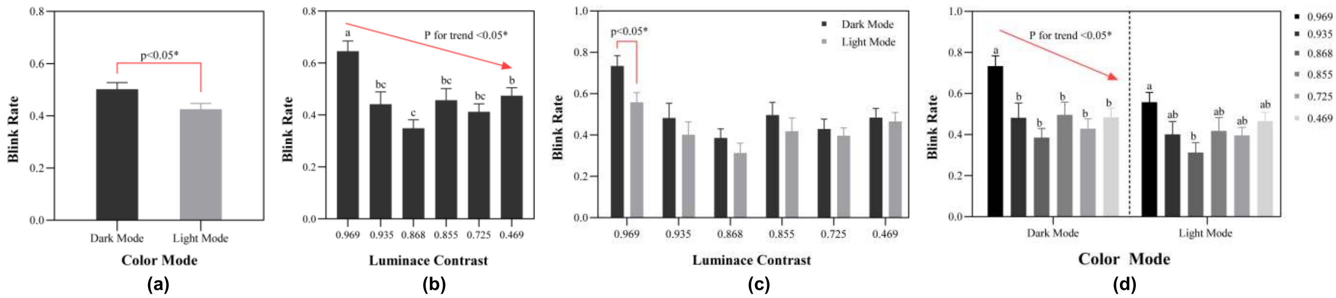

FIGURE 5. (a) BR in different color modes, (b) BR in different luminance contrast, (c) (d) Interaction between color mode and luminance contrast.

TABLE 3. Means and standard deviations for each dependent variables under different experimental conditions.

Dependent variables	Independent variables											
	D.M. 0.969	D.M. 0.935	D.M. 0.868	D.M. 855	D.M. 0.725	D.M. 0.469	L.M. 0.969	L.M. 0.935	L.M. 0.868	L.M. 0.855	L.M. 0.725	L.M. 0.469
BR	0.734 (0.158)	0.482 (0.227)	0.385 (0.141)	0.496 (0.195)	0.429 (0.153)	0.484 (0.142)	0.558 (0.151)	0.401 (0.199)	0.313 (0.150)	0.418 (0.206)	0.396 (0.123)	0.465 (0.137)
PA	0.044 (0.017)	0.031 (0.014)	0.022 (0.021)	0.025 (0.018)	0.014 (0.009)	0.022 (0.017)	0.015 (0.011)	0.011 (0.008)	0.011 (0.009)	0.017 (0.015)	0.014 (0.008)	0.012 (0.010)
VFS	19 (4.62)	20.50 (8.20)	14.6 (5.78)	15.4 (4.17)	13.2 (5.22)	18.5 (6.72)	11.6 (3.69)	12.4 (5.52)	12.2 (5.01)	14.9 (5.09)	12.0 (4.76)	19.2 (7.61)
SP	2.9 (0.74)	3.8 (1.40)	4 (1.05)	4.3 (1.34)	4.7 (1.16)	3.2 (1.48)	5.1 (0.57)	4.5 (1.27)	4.3 (0.95)	4.2 (0.79)	4.5 (1.51)	3.3 (1.70)

(text-background) luminance contrast [F (5, 114) = 7.024, $P < 0.0001$. $\eta^2 = 0.245$] had significant effects on the blink rate. No significant interaction between the color mode and the luminance contrast was found [F (5, 114) = 0.535, $P > 0.05$, $\eta^2 = 0.749$] (Fig. 5c).

Duncan multiple paired-comparisons showed that the blink rate in the dark mode was significantly higher than that in the light mode (Fig. 5a). For the luminance contrast, 0.969 resulted in the highest blink rate, followed by 0.469, 0.935, 0.855, 0.725, and 0.868. Pearson correlation analysis found that Pearson correlation coefficient (i.e., PCCs) = − 0.216, with significance $P = 0.018 < 0.05$ (Fig. 5b).

In the dark mode, when the luminance contrast was 0.969, the blink rate was significantly higher than other luminance contrast. Pearson correlation analysis found that there was a significant negative correlation between luminance contrast and blink rate in the dark mode. In the light mode, the blink rate was the highest when the luminance contrast was 0.969 (Fig. 5d).

B. PUPIL ACCOMMODATION

The results of MANOVA showed that both the color mode [F (1, 118) = 27.928, $P < 0.001$, $\eta^2 = 0.205$] and the (text-background) luminance contrast [F (5, 114) = 3.208, $P < 0.05$, $\eta^2 = 0.129$] had significant effects on the pupil accommodation. There was a significant interaction between color mode and luminance contrast [F (5, 114) = 2.796, $P < 0.05$, $\eta^2 = 0.115$].

Duncan multiple paired-comparisons showed that the pupil accommodation was significantly faster in the dark mode than that in the light mode (Fig. 6a). For the luminance contrast, 0.969 resulted in the fastest pupil accommodation, followed by 0.935 and 0.855, finally 0.868, 0.725, and 0.469 (Fig. 6b). Pearson correlation analysis of luminance contrast and pupil accommodation showed that $PCCs = -0.245$, with significance $P = 0.007 < 0.05$.

As to the interaction between color mode and luminance contrast, the pupil accommodation was faster in the dark mode than that in the light mode under the six luminance contrast ratios. The difference was significant only in 0.969 and 0.935 (Fig. 6c). In the dark mode, 0.969 resulted in the fastest pupil accommodation, followed by 0.935, 0.868, 0.855, and 0.469. The luminance contrast of 0.725 resulted in the slowest pupil accommodation. In the light mode, there was no significant difference among different luminance contrast (Fig. 6d). Overall, dark mode, 0.969 luminance contrast resulted in the fastest pupil accommodation, followed by dark mode, luminance contrast 0.935. Light mode, luminance contrast 0.935, 0.868, 0.469 resulted in the slowest pupil accommodation.

C. VISUAL FATIGUE SCALE

The results of MANOVA showed that both the color mode [F (1, 118) = 8.831, $P < 0.001$, $\eta^2 = 0.076$] and the (text-background) luminance contrast [F (5, 114) = 3.089, $P < 0.05$, $\eta^2 = 0.125$] had significant effects on visual fatigue scale. There was no significant interaction between

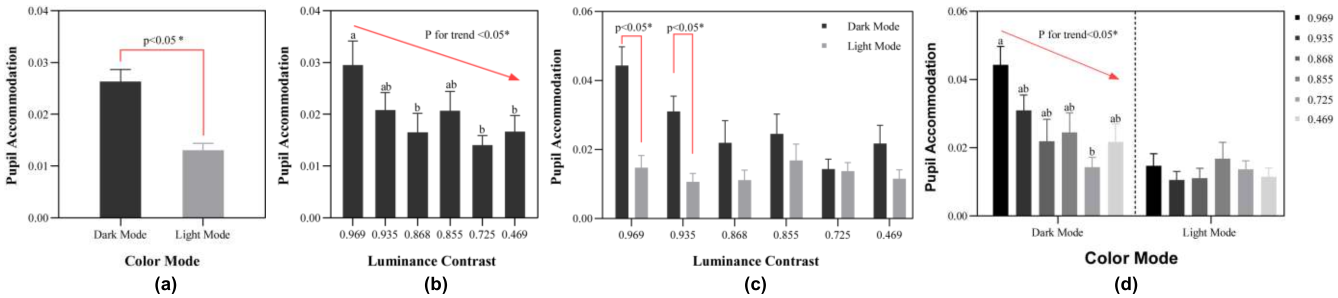

FIGURE 6. (a) PA in different color modes, (b) PA in different luminance contrast, (c) (d) Interaction between color mode and luminance contrast.

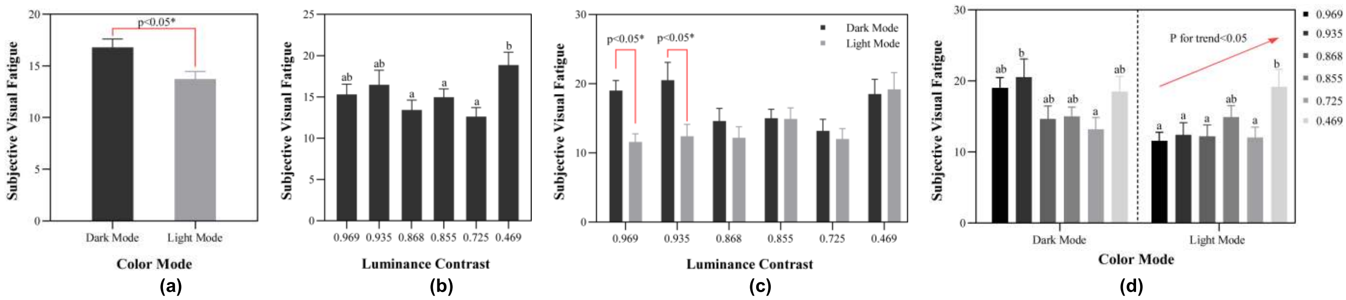

FIGURE 7. (a) VFS in different color modes, (b) VFS in different luminance contrast, (c) (d) Interaction between color mode and luminance contrast.

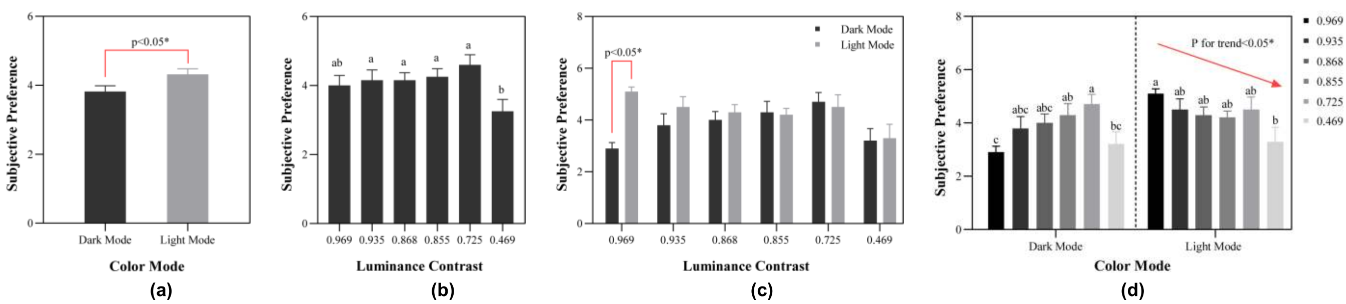

FIGURE 8. (a) SP in different color modes, (b) SP in different luminance contrast, (c) (d) Interaction between color mode and luminance contrast.

color mode and luminance contrast [F (5, 114) = 2.199, $P = 0.06$] (Fig. 7c).

Duncan multiple paired-comparisons showed that the visual fatigue scale in the light mode was significantly lower than that in the dark mode (Fig. 7a). As to the luminance contrast, 0.868, 0.855, 0.725 resulted in the lowest visual fatigue scale, followed by 0.969, 0.935, 0.469 (Fig. 7b).

In the dark mode, the luminance contrast of 0.725 resulted in the lowest visual fatigue scale, followed by 0.868, 0.855, finally 0.969, 0.935, 0.469. In the light mode, the luminance contrast of 0.969, 0.935, 0.868 resulted in the lowest visual fatigue scale. The luminance contrast of 0.469 resulted in the highest visual fatigue scale. And there was a significant positive Pearson correlation between luminance contrast and visual fatigue scale in the light mode (Fig. 7d).

D. SUBJECTIVE PREFERENCE

The results of MANOVA showed that both the color mode [F (1, 118) = 5.127, $P < 0.001$, $\eta^2 = 0.045$] and the (text-background) luminance contrast [F (5, 114) = 2.743, $P < 0.05$, $\eta^2 = 0.113$] had significant effects on the subjective preference score. There was a significant interaction between color mode and luminance contrast [F (5, 114) = 2.721, $P < 0.05$, $\eta^2 = 0.112$].

Duncan multiple paired-comparisons showed that the subjective preference score in the light mode was significantly higher than that in the dark mode (Fig. 8a). For the luminance contrast, 0.935, 0.868, 0.855, 0.725 resulted in the highest subjective preference, followed by 0.969, 0.469 (Fig. 8b).

As to the interaction between color mode and luminance contrast, the subjective preference in the light mode was higher than that in the dark mode when luminance contrast was 0.969, 0.935, 0.868, 0.469. When the luminance contrast was 0.855 and 0.725, the subjective preference in the dark mode was higher. These differences were significant only when the contrast was 0.969 (Fig. 8c). In the dark mode, the luminance contrast of 0.725 resulted in the highest subjective preference, followed by 0.868, 0.855, finally 0.969, 0.469. In the light mode, the luminance contrast of 0.969 resulted in the highest subjective preference, followed by 0.725, 0.935, 0.868, 0.855. The luminance contrast of 0.469 resulted in the lowest subjective preference. we found there was a significant negative correlation between luminance contrast and subjective preference in the light mode (Fig. 8d). Overall,

TABLE 4. Pearson correlation tests for dependent variables.

	BR	PA	VFS	SP
BR	1			
PA	0.309*	1		
VFS	0.173	0.248*	1	
SP	-0.025*	-0.279*	-0.591*	1

* indicates a significant correlation at the 0.05 level.

light mode, 0.969 and dark mode, 0.725 resulted in the highest subjective preference. Light mode, 0.469 and dark mode, 0.969, 0.469 resulted in the lowest subjective preference.

Pearson correlation analysis was used to test the correlation between different dependent variables (Table 4). There was a significant Pearson positive correlation between blink rate and pupil accommodation ($PCCs = 0.309$, significance $P = 0.001$). It indicated that pupil accommodation was slower when the blink rate was lower under different experimental conditions. In other words, the two objective indicators showed the consistency in the detection of visual fatigue. There was a significant negative correlation between visual fatigue scale and subjective preference ($PCCs = -0.591$, significance $P = 0.000$). It meant that subjective preference was lower when visual fatigue scale was higher—that is, there was consistency between the two subjective indicators. Unfortunately, we did not find the consistency between subjective and objective indicators.

IV. DISCUSSION

In order to reduce the visual fatigue caused by using electronic screens at night, this paper studied the eye protection mode. The aim of the study was to investigate the conjoint impacts of color mode and luminance contrast on visual fatigue under low screen luminance and low ambient illumination at night. We used a multidimensional approach based on eye and subjective measurements.

The data analysis results of color mode, luminance contrast, and the interaction (color mode ∗ luminance contrast) are discussed below.

A. COLOR MODE

About color mode, results of objective indicators indicated that using electronic screens in the dark mode leads to an increase in BR and PA with respect to the light mode. It meant that objectively the dark mode resulted in less visual fatigue. This result is in line with the conclusions of Rempel and Mautiuk [12], Ericson *et al.* [13], Mantiuk *et al.* [32], Kim *et al.* [33], and Jiang *et al.* [34].

The results of subjective indicators indicated that VFS was significantly higher and SP was significantly lower in the dark mode than that in the light mode. It is consistent with the results of some studies on the subjective preference of positive and negative polarities—that is, the subjects show higher SP and lower VFS for positive polarity [35]. This result may be related to the familiarity effect—that is, the subjects prefer positive polarity texts and tend to show lower subjective visual fatigue score due to accumulated perceptual experience and using habits of paper texts (black words on a white background) [16], [34].

The results of objective indicators and subjective indicators were not consistent. In the follow-up study, subjects with rich experience in the use of the dark mode should be selected for the experiment, so as to further verify this conclusion.

B. LUMINANCE CONTRAST

As to luminance contrast, results of objective indicators revealed that it had significant effects on the BR and PA. The luminance contrast of 0.969 resulted in the highest BR and the fastest PA—that is, objectively 0.969 resulted in the lowest visual fatigue when using electronic devises at night. The luminance contrast of 0.935, 0.855, 0.725 resulted in higher BR and faster PA. The luminance contrast of 0.868, 0.469 resulted in the lowest BR and the slowest PA. So, for the design of eye protection mode, we suggest that (text-background) luminance contrast should be 0.969, 0.935, 0.855, and 0.725 under low screen luminance and low ambient illumination at night. Furthermore, the results of Pearson correlation analysis showed that there was a significant negative correlation between luminance contrast and BR, PA. This suggested that higher luminance contrast led to lower visual fatigue, which is consistent with the conclusions of Na and Suk [15], Lin and Huang [16], and Ayama *et al.* [36].

In the subjective indicators, results showed that the luminance contrast of 0.868, 0.855, and 0.725 resulted in lower VFS and higher SP, followed by 0.969, 0.935. The luminance contrast of 0.469 resulted in the highest VFS and the lowest SP. Only the differences between 0.469 and the other contrast ratios were statistically significant. Thus, low luminance contrast resulted in the highest VFS and the lowest SP under low screen luminance and low ambient illuminance at night.

Overall, both the results of objective indicators and subjective indicators showed higher luminance contrast ratios were more conducive to reducing visual fatigue and subjects also preferred higher luminance contrast. In the eye protection mode, the (text-background) luminance contrast lower than 0.469 should be avoided.

C. INTERACTION (COLOR MODE * LUMINANCE CONTRAST)

This section describes the interaction between color mode and luminance contrast. The interaction was significant in two indicators: PA and SP, not significant in BR and VFS.

In the dark mode, the luminance contrast of 0.969 led to an increase in the BR and PA. The results of Pearson correlation analysis showed that the luminance contrast was positively correlated with BR and PA. This meant in the dark mode (light words on a dark background), higher luminance contrast reduced visual fatigue. As to subjective indicators, the luminance contrast of 0.868, 0.855, 0.725 resulted in lower VFS and higher SP. When the luminance contrast ratios were higher than 0.868 or less than 0.725, the VFS increased and SP decreased—that is, the subjects preferred moderate luminance contrast in the dark mode. The conclusion of subjective indicators is consistent with that of Ou *et al.* [19]. Overall, in the objective indicators and subjective indicators, it was consistent when the luminance contrast was lower than 0.725. It was inconsistent when the luminance was higher than 0.935, objective indicators showed lower visual fatigue, whereas subjective indicators showed higher visual fatigue and lower subjective preference. This inconsistency remains to be studied.

In the light mode, the luminance contrast of 0.969 resulted in the highest BR and the fastest PA, which mean the lowest visual fatigue. As to subjective indicators, the subjects preferred the luminance contrast of 0.969, 0.935, and 0.868. When the luminance contrast was 0.469, the VFS was the highest and SP was the lowest. Results of Pearson correlation analysis showed that there was a significant negative correlation between luminance contrast and VFS, a significant positive correlation between luminance contrast and SP. Overall, in the objective indicators and subjective indicators, higher luminance contrast resulted in higher preference and it was also conducive to reducing visual fatigue. We suggest that luminance contrast ratios higher than 0.868 should be used in the design of the light mode. This conclusion is consistent with the conclusion of Ou *et al.* [19].

In this study, we found the BR and PA were consistent in detecting visual fatigue, which is consistent with previous research results. The VFS was consistent with SP. However, we did not find complete consistency between objective indicators and subjective indicators.

V. CONCLUSION

In conclusion, results showed that in the night eye protection mode, both the color mode and luminance contrast had significant influences on visual fatigue and subjective preference. The dark mode (i.e., presenting light texts on a dark background) is more conducive to reducing visual fatigue. Subjects showed a higher preference in the light mode (i.e., presenting dark texts on a light background), which may be related to their usage habits. Higher luminance contrast ratios (0.969, 0.935, 0.855) help reduce visual fatigue and people also prefer higher luminance contrast. The luminance contrast of 0.469 may induce the highest visual fatigue. In the design of the light mode, we suggest the (text/background) luminance contrast should be 0.969 and 0.935. In the dark mode, the luminance contrast of 0.969 resulted in the lowest visual fatigue, whereas subjects preferred 0.868, 0.855, 0.725. The dark mode with the (text-background) color luminance contrast of 0.969 is the most conducive to reducing visual fatigue.

This paper expands on and reinforces the theoretical research on eye protection mode in a dim environment at night. And the study has three applications. Firstly, this paper provides the suggestion for users of electronic displays. We suggest that users should adjust display color mode to the dark mode to protect their eyes when using mobile phones or tablets under low screen brightness after turning off the lights at night. Secondly, this study provides designers with some guidelines for the design of interaction interface of the electronic devices when the ambient illumination is lower than 3lux and the screen luminance is 28cd/m^2(5%screen brightness). Applications etc. should not use the (text-background) luminance contrast lower than 0.725 at night. Thirdly, this conclusion can also provide some references for the interactive interface design of head-mounted displays (HMDS) to obtain a better visual experience. Since the objective indicators and subjective indicators did not get completely consistent results, in subsequent studies, subjects with dark mode experience should be selected for further verification of this conclusion.

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