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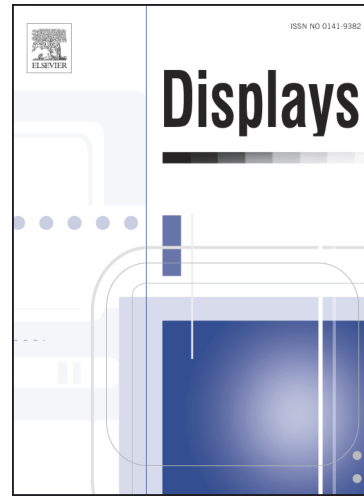

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Chin-Chiuan Lin, Kuo-Chen Huang

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Effects of ambient illumination conditions and background color on visual performance with TFT-LCD screens

Chin-Chiuan Lin [a,*], Kuo-Chen Huang [b]

[a] *Department of Business Administration, Kun-Shan University, Tainan, Taiwan*

[b] *Department of Product Design, Ming-Chuan University, Taipei, Taiwan*

[*]Corresponding author.

Tel.: +886 6 2050542 ext 25;

Fax: +886 6 2050543;

E-mail: cclin@mail.ksu.edu.tw.

Department of Business Administration, Kung-Shan University

949, Da-Wan Road, Yung-Kang District,

Tainan City, 710, Taiwan, R.O.C.

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Abstract

This study investigated the effects of ambient illumination conditions (illumination color and illumination intensity) and background color on visual performance (character identification and reading comprehension) with TFT-LCD screens.

Results of Experiment 1 indicated that all the three independent variables had significant effects on mean percentage of character identification. Mean character identification performance was best under white light, 500 lux, and blue background. In general, the backgrounds with primary colors had better mean character identification performance than the middle-point colors and gray. Results of Experiment 2 indicated that the illumination intensity and background color had significant effects on mean text comprehension performance for reading comprehension. Mean text comprehension performance were higher under 500 lux and blue background. The backgrounds with primary colors had better mean correct answers than the gray background. According to the results, white light, normal ambient illumination and a background with primal colors seemed to be the optimal conditions. If the yellow ambient light is necessary, using blue as the TFT-LCD background color of will provide better performance.

The Pearson product-moment correlation coefficient indicated that short-term visual task measurement might be suitable to evaluate the visual performance.

Keywords: Ambient illumination conditions; Background color; Visual performance

1. Introduction

Thin film transistor liquid-crystal displays (TFT-LCD) with light emitting diode (LED) or cold cathode fluorescent lamp (CCFL) backlighting are now becoming the optimal choice for visual display terminals (VDT) due to their low power consumption, rapid price reduction, improved optical characteristics and large variety of display size.

Ambient illumination conditions (illumination color and illumination intensity) significantly affect human psychological responses, such as visual performance [1,2], color discrimination [3,4] and visual workload [5]. To support the various purposes of a workplace, the illumination colors of fluorescent lamps may vary; for instance, white light in used for general offices and yellow light for the etching process in photo areas of semi-conductor factories. Lin et al. [5] reported that both visual acuity and subjective visual fatigue were significantly affected by the color of light. But there are insufficient studies on the effects of illumination color on visual performance.

Illumination intensity is an important consideration in TFT-LCD workstation design. In addition to the effects of illumination intensity on screen luminance, the surface-reflected light also affects the chromaticity coordinates of colors [3]. Furthermore, under usual ambient illumination conditions for working with a TFT-LCD (notebook computer screen), illumination intensity can vary greatly, e.g., in an office or outdoors. Thus, there is a need to further examine the effects of illumination intensity on visual performance using TFT-LCD.

Chromaticity contrast (background color) is an important subfactor of color combination and can be an effective way of improving human-computer communication [1,6-8]. Though chromaticity contrast can improve visual performance, some color combinations may cause added visual problems due to chromatic aberration [9]. Further, Buchner and Baumgartner [10] showed that chromaticity contrast could not compensate for a lack of luminance contrast, and luminance contrast of the screen is the most important subfactor of color combination [1] that significantly affects visual performance [1,6,11-16]. Generally, a higher luminance contrast results in better visual performance, but in order to reduce power consumption, the ratio of 8:1 might be the optimal choice of luminance contrast [1,11].

Polarity is another subfactor of color combination that may affect visual performance. Positive polarity is the most commonly used polarity many software programs, and most research has indicated that positive polarity produces better visual performance than negative polarity [10,17-19]. But most previous studies have confounded the effects of luminance contrast with those of chromaticity contrast and polarity. Therefore, the present study uses positive polarity and a luminance contrast of 8:1 to examine the effects of chromaticity contrast on TFT-LCD screens.

In summary, there is a lack of studies concerning the effects of ambient illumination conditions (illumination color and illumination intensity) and background color both for short-term visual task (character identification) and for long-term visual task (reading comprehension) with TFT-LCD are rare. Therefore, it is important to empirically evaluate the effects of ambient illumination conditions and background color on visual performance when using TFT-LCD.

2. Experiment 1: Short-term Visual Task-- Character Identification

2.1. Experimental design

The experiments in this study evaluated three independent variables: illumination color, illumination intensity and chromaticity contrast.

Two levels of illumination color were tested, white light used for general offices and yellow light for the etching process in photo area of semi-conductor factories.

Four levels of illumination intensity were tested: 250 lux (low-level office illumination), 500 lux (normal office illumination), 1000 lux (high-level office illumination) and 2000 lux (precision work illumination). Extreme levels of illumination intensity, i.e., 50 lux or 10000 lux were not used because they are not practical for normal office visual tasks, although considering those levels might also lead to significant findings.

Seven background colors were employed, including the three primary colors (red, green and blue), the three middle-point colors (yellow, cyan and purple), and a center-point one (gray) in the CIE chromaticity coordinates. The seven colors used were selected according to the criteria that their maximum luminance would be at least 40 cd/m^2 and the set of colors should be distributed evenly and widely in the chromaticity space. Table 1 show the CIE coordinates (*L*, *x*, *y*) and the RGB code value of the background and text colors.

Insert Table 1 about here

2.2. Subjects

Forty students (20 female and 20 male) from Kun-Shan University were enrolled as subjects (age range = 19-23 years). All had at least 0.8 corrected visual acuity or better and normal color vision. A Topcon SS-3 Screenscope and standard Pseudo-Isochromatic charts were employed to test the visual acuity and the color vision of the subjects, respectively.

All subjects completed 56 combinations (2 illumination color × 4 illumination intensity × 7 background color).

2.3. Apparatus

A 17-in., CMV 745A TFT-LCD with a 433-mm diagonal screen provided an active viewing area of 338 mm horizontally and 272 mm vertically. The pixel resolution was 1024 horizontally and 768 vertically, and the center-to-center pixel spacing was about 0.35 mm. The screen images were refreshed at a rate of 72 Hz. The maximal luminance contrast ratio value and maximal luminance of the TFT-LCD were about 150 and 210 cd/m^2, respectively. The screen surface was coated with SiO_2 polarizer to reduce glare and reflection.

Fluorescent lamps for white light were 40 W FL40D/38 and for yellow light were 40 W F36/16CR. White light and yellow light fluorescent lamps were purchased from the Taiwan Fluorescent Lamp Co. Ltd. (Taiwan) and the Shun Trade Co. Ltd. (Taiwan), respectively.

CIE values of the TFT-LCD screen were measured using a Laiko Color Analyzer DT-100. The illumination intensity was measured using a TES-1330 digital lux meter.

2.4. Workplace condition

The TFT-LCD was positioned on a table 70 cm in height. The inclination angle of the TFT-LCD screen was 105º [20-22] with respect to the vertical axis. A headrest restrained each subject’s head at 25 cm above the table and maintained their viewing distance at 55 cm during the experiment. There was no glare on the TFT-LCD screen.

2.5. Task and procedure

Subjects performed a character identification task. At the beginning of each trial, a warning tone was initiated to instruct the subject to visually fixate on an "X" at the center of the screen. A few seconds later (uniform distribution ranged from 2 to 6 s), a stimulus composed of four [23] capital English letters was presented in the center area of the screen for 200 ms (approximately one eye-fixation duration). The subjects were required to write as many letters as they could identify in the corresponding position within 10 seconds. The four capital English letters were presented at the corners of an area approximately 20 mm × 20 mm at the center of the screen. The height for the 12-point letters was about 4.2 mm. The subtended visual angle of the letters was about 25 min of arc.

There was one capital English letter set (A-Z) for each position. Each letter was presented once in each position. There were 26 trials for each treatment. For the first trial, the computer randomly selected one capital English letter from the letter set for each of positions 1, 2, 3 and 4, respectively. Then the presented letters were deleted from the letter set for that position and recorded in a file. In the second trial, the computer again randomly selected one letter from the remaining letter sets for positions 1, 2, 3 and 4 again. The procedure was repeated iteratively until the letter sets were empty.

To familiarize the subjects with the character identification task, they performed five training trials for each treatment, and each treatment took about 4 min. There was a 1-2 min break between treatments to avoid successive contrast effects and visual fatigue. The overall experiment lasted about 4 hr for each subject, including regular breaks to reduce fatigue. For each subject, the three within-subject factor treatments were administered randomly. Before the experiment, the treatment sequence for each subject was determined by drawing lots. To maintain work motivation, subjects were paid NT$ 100 per hr, plus an extra NT$ 100 if their overall average percentage of correctly identified letters exceeded 60%.

2.6. Performance measures and data analysis

The percentage of correctly identified letters was used as the short-term visual performance measure. The correctness was checked by the computer recorded file and the subjects' writing sheet. The correctness was also determined by the position sequence of recall. For example, if the presented position sequence from a particular trial was BMSQ, then the response of MSQB would not be correct.

In the present study, the mean percentages (mean of correct character identification percentage) for all of the 20 female and the 20 male subjects together were used instead of individual character identification performance to avoid the confounding of subjects' difference.

According to previous studies, the range of illumination intensity between 50 and 3000 lux affected neither the change of critical flicker frequency (CFF) nor subjective visual fatigue [24,25]. Therefore, the present study did not measure the CFF and subjective visual fatigue. Analysis of multivariate (MANOVA) was conducted using the Statistical Analysis System (SAS).

2.7. Results of experiment 1

The mean character identification performance values under each level of independent variables are shown in Table 2. The results of MANOVA for the mean character identification performance of independent variables (Table 3) indicated that all main effects, namely illumination color ($F_{1,55} = 487.55$, $p < 0.0001$), illumination intensity ($F_{3,55} = 202.12$, $p < 0.0001$) and background color ($F_{6,55} = 75.49$, $p < 0.0001$) had significant impact on the mean character identification performance. Further, the effect size [26,27] showed that illumination intensity ($\eta^2 = 0.27$) had the most significant impact on the mean character identification performance, followed by illumination color ($\eta^2 = 0.22$), and background color ($\eta^2 = 0.21$). The corrected model F-value of 38.28 implies that the model is significant ($p < 0.0001$).

Duncan multiple paired-comparisons (Table 2) indicated out that the MP for white light (77.2%) was significantly greater than that for yellow light (74.1%). For illumination intensity, 500 lux (78.1%) resulted in the best mean character identification performance, followed by 250 lux (76.4%), 1000 lux (74.9%) and 2000 lux (73.4%). For background color, blue (78.4%) background resulted in best mean character identification performance, followed by green (76.7%), red (76.3%), gray (75.3%), cyan (75.1%), yellow (74.4%) and purple (73.5%). In summary, a primary colors background provided better character identification performance than one with the middle-point colors or gray.

Insert Table 2 about here

Insert Table 3 about here

Interaction effects of the three independent variables all reached statistically significant levels (Table 3). Overall, white light, 500 lux and blue background resulted in the best character identification performance; yellow light, 2000 lux and background with purple and cyan color resulted in the worst character identification performance. The analysis of interaction effects of the illumination color × illumination intensity showed that the white light and 500 lux resulted in the best mean character identification performance (78.2%) and yellow-light and 2000 lux resulted in the worst mean character identification performance (71.2%); the interaction effects of the illumination color × background color showed that the blue background under white light resulted in the best character identification performance (79.1%) and purple background under yellow-light resulted in the worst MP (71.9%); the interaction effects of the illumination intensity × background color showed that the blue background under 500 lux resulted in the best mean character identification performance (80.5%) and purple background under 2000 lux resulted in the worst mean character identification performance (71.1%).

3. Experiment 2: Long-term Visual ask-- Reading Comprehension

3.1. Method

One month after the completion of Experiment 1, twenty students (10 female, 10 male) who had better mean character identification performance were selected from Experiment 1 to serve as subjects for Experiment 2.

The experimental apparatus and workplace conditions were the same as those used in Experiment 1, except as noted below. In this experiment, illumination color, illumination intensity, and background color were again independent variables. Two levels of illumination color were tested, white light and yellow light. Three levels of illumination intensity were tested, 250, 500 and 1000 lux. For chromaticity contrast, four background colors were employed, including the three primary colors (red, green and blue), and a center-point color (gray) in the CIE chromaticity coordinates. The CIE chromaticity coordinates of the four colors used were same as in Experiment 1. All subjects completed 24 combinations (2 illumination color $\times$ 3 illumination intensity $\times$ 4 background color).

3.2. Task and procedure

Subjects were instructed to perform a long-term reading task, and an individual experimental session consisted of the following sequence of events. There were 24 articles. Each article contained 23 screen-pages and each page was presented on the screen for 2 min (46 min for the entire article). Articles were assigned randomly for the 24 treatments of each subject.

The articles were presented in Chinese. The characters were displayed with the font

"ET" in 15 × 16 dot matrices. The height and width of the characters were about 5.3 mm × 5.6 mm. The characters per screen for the text were arranged in 18-20 lines, with 30 characters per line. The inter-character spacing was about 0.7 mm, and inter-line spacing was about 1.4 mm. The height and width of the area used for the text presentation was about 140 mm × 180 mm.

Subjects were required to read the article and complete a 10-item comprehension test in 10 min at the end of the experimental session. For each subject, three within-subject factor treatments were administered randomly. Before the experiment, the treatment sequence for each subject was determined by drawing lots. To maintain work motivation, subjects were paid NT$ 100 per hour, plus an extra NT$ 5 for each correct answer on the comprehension test.

3.3. Dependent measures and data analysis

Long-term visual performance was defined as the number of correct answers of the reading comprehension test. Again, the mean answer (mean of correct answers on the 10-item comprehension test) of the 10 female and 10 male subjects were used instead of individual number of correct answers to avoid the confounding of subjects' difference. Analysis of multivariate (MANOVA) was conducted using Statistical Analysis System (SAS).

3.4. Results of experiment 2

The text comprehension performance values under each level of independent variables are shown in Table 2. The results of MANOVA for the text comprehension performance of independent variables (Table 3) indicates that only illumination intensity ($F_{2,23} = 7.98$, $p = 0.0023$) and background color ($F_{3,23} = 6.26$, $p = 0.0029$) had significant impact on the mean text comprehension performance. Though white light resulted in slightly better mean text comprehension performance than yellow light, the difference did not reach statistical significance ($p < 0.01$). Further, the effect size showed that background color ($\eta^2 = 0.24$) had the most significant impact on the mean text comprehension performance, followed by illumination intensity ($\eta^2 = 0.21$), and illumination color ($\eta^2 = 0.07$). The corrected model F-value of 2.25 implies that the model is significant ($p = 0.0283$).

Duncan multiple paired-comparisons (Table 2) indicated that the text comprehension performance for illumination intensity of 500 lux (7.5) resulted in the highest mean text comprehension performance, followed by 250 lux (7.0) and 1000 lux (6.9). The blue (7.5) background resulted in the best mean text comprehension performance, followed by green (7.4), red (7.1) and gray (6.7). The background with the primary colors had better mean text comprehension performance than the gray background.

None of the interaction effects of the three independent variables reached a statistically significant level ($p < 0.01$).

4. Discussion

The experimental results are discussed below with regard to illumination color, illumination intensity, background color and interaction effects having statistically significance.

4.1. Illumination color

The MANOVA results showed that illumination color did affect significantly character identification performance. White light resulted in better character identification performance than yellow light. But the illumination color slightly shifted the color coordinates (x, y) of background colors. For instance, the x-value and y-value of background color coordinates (x, y) under yellow light were slightly greater than those under white light. The shift in x-value and y-value increased the ΔE [28] of red, purple and yellow and might increase character identification performance under yellow light. But the increase of the ΔE was very slight and so it did not significantly affect character identification performance. This result might have been because the subjects were more accustomed to the white light than yellow light condition because white light is the more common illumination color for general offices.

But in contrast, the MANOVA results showed that illumination color did not significantly affect mean text comprehension performance. Chung and Pease [29] showed that the pupil size is larger under yellow light than with luminance-matched white light. However, enlarged pupils over a long period might increase eye fatigue, though it did not significantly affect mean text comprehension performance in this case.

4.2. Illumination intensity

MANOVA results showed that illumination intensity did significantly affect visual performance (character identification performance and text comprehension performance). Visual performance under normal illumination intensity (500 lux) was better than that under other intensities. For the design of illumination intensity, the American Illumination Engineering Society [30] suggests that illumination level for general office work should be 750 lux, while the German DIN is 500 lux. These result are consistent with Läubli et al. [31] and Stammerjohn et al. [32], who found that most VDT offices are within the range of 30-500 lux and they are also consistent with results obtained by previous studies [2,14,29,33] that illumination intensity did affect significantly visual performance.

First, the screen luminance of a given TFT-LCD is affected by illumination intensity [14,29,34], so high illumination intensity may cause screen images to fade due to screen brightness [35]. Second, the actual luminance contrast ratio percentage decreased with increasing illumination intensity [33] because of surface reflection. With higher illumination intensity, there was a greater percentage decrease in luminance contrast [14]. These two reasons may explain why the subjects had better visual performance at 500 lux than at 1000 lux and 2000 lux.

However, compared with normal illumination intensity (500 lux), low-level illumination intensity (250 lux) was not associated with better visual performance. First, the effect of illumination intensity might have been obscured under relatively low level illumination, because the luminance of reflected illumination intensity and the decrease in percentage of luminance contrast were very slight. For example, the luminance reflected for the 250 and 500 lux levels was only about 0.3 and 0.5 cd/m^2, respectively. Therefore, the effect of luminance of reflected illumination intensity was obscured, though the normal illumination intensity might result in slightly greater direct reflected light than low-level illumination intensity [36]. Second, the low-level illumination intensity may cause more visual fatigue than normal illumination intensity, thus decreasing visual performance.

4.3. Background color

MANOVA results showed that background color did significantly affect visual performance (character identification performance and text comprehension performance). Blue background resulted in best character identification performance, followed by green, red, cyan, gray, yellow, and purple in Experiment 1. Overall, the primary colors (blue, green, and red) also seemed to promote better character identification performance than the middle-point colors (cyan, yellow, and purple) and gray. This result is consistent with the findings of Lin and Huang [14] that the primary colors had better perception time than the middle-point colors. The blue background also resulted in better text comprehension performance, followed by green, red, and gray in Experiment 2. This result also is consistent with previous findings [1,14] that background color can improve visual performance.

Three reasons may be offered. First, with reduced of color saturation, the blue primary is more visible than red or green [37]. Thus subjects were more able to accept a decreased saturation for the blue primary than for the other two primaries. Second, when the colors are presented on a screen simultaneously under normal presentation conditions, the middle-point colors have higher luminance than the primary colors. For instance, under normal presentation conditions, the luminance of yellow (middle-point color) and blue (primary color) were about 100 and 10 cd/m^2, respectively. When the luminance was at 40 cd/m^2 level, the middle-point colors had reduced brightness and saturation. In contrast, when the luminance was at 40 cd/m^2 level, the primary colors had increased brightness and saturation. Hence, the middle-point colors appeared more turbid and dim than at normal luminance levels, leading to reduced legibility (Table 4).

Insert Table 4 about here

Third, Lippert [28] proposed that the ΔE scale could provide good prediction of legibility performance. Since the ΔE scales are smaller for the middle-point colors than for the primary colors under the same luminance, their lower small ΔE also resulted in worse MP for the middle-point colors.

In summary, chromatic backgrounds with primary colors had better visual performance than monochromatic or middle-point colored backgrounds.

4.4. Interaction effects

Though the interaction effects of the three independent variables all reached statistically significant levels in character identification performance (Table 3), the effect size showed that the interaction effects of the three independent variables are very slight. The effect size of illumination color × illumination intensity, illumination color × background color and illumination intensity × background color was only 0.07, 0.05 and 0.03, respectively.

Despite the small effect size of the interaction effects of the three independent variables, compared to white light, the yellow background color had smallest decrease in character identification performance under yellow light than other background colors. Two reasons might be offered to explain this result. First, Rabin and Wiley [38] proposed that yellow light provided only slight enhancement for the apparent contrast of yellow compared to black. Therefore, yellow light might increase the brightness and saturation of a yellow background, thus increasing character identification performance. Second, the x-value and y-value of the yellow background color were greater than those values under white light. An increase in x-value and y-value also increases the ΔE of yellow background color, which in turn increases character identification performance. However, the blue background had best character identification performance than others.

In contrast, none of the interaction effects of the three independent variables reached a statistically significant level in text comprehension performance ($p < 0.01$).

The Pearson product-moment correlation coefficient ($r = 0.39$, $p = 0.0062$) indicated that character identification performance (short-term) was significantly related to text comprehension performance (long-term). This result indicates that in order to save experimental time, the short-term visual task measurement might be more suitable for evaluating the visual performance instead of long-term task measurement.

5. Conclusion

Visual performance was significantly affected by three independent variables. For the current TFT-LCD, our results imply that under equivalent and low screen luminance conditions, white light, 500 lux illumination and a background of a primary color were the better visual task setting conditions in an office setting. Further, the effect size shows that the illumination intensity has the greatest impact on short-term visual tasks and background color has the most significant impact on long-term visual tasks. If yellow light is necessary (e.g. for the etching process in the photo area of semi-conductor factories), under equivalent screen luminance condition, it is better to use blue as the TFT-LCD background color.

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Table captions

Table 1 CIE (1931) chromaticity coordinates of background and text color.

Table 2 Mean character identification performance and mean text comprehension performance for each level of independent variables and Duncan grouping.

Table 3 MANOVA for mean character identification performance and mean text comprehension performance of independent variables

Table 4 Different luminance of background color present on the screen.

Table 1

CIE (1931) chromaticity coordinates of background and text color.

Color	Code	CIE(L, x, y)			RGB code value		
		L	x	y	R	G	B
Background	Red	40	6387	3505	222	0	0
	Green		2870	5885	0	158	0
	Blue		2081	1795	92	92	254
	Yellow		4715	4603	145	118	0
	Purple		3515	2327	198	0	203
	Cyan		2416	3379	0	146	125
	Gray		3305	3337	150	135	127
Text	Gray	5	3301	3340	82	65	53

Note: The CIE coordinates were measured using a Laiko Color Analyzer DT-100 in a darkroom.

Table 2

Mean character identification performance and mean text comprehension performance for each level of independent variables and Duncan grouping.

Experiment	Independent variable	n	Mean	SD	Duncan grouping				
Mean character identification performance	Illumination color								
	White light	56	77.2	2.4	A				
	Yellow light	56	74.1	3.4		B			
	Illumination intensity								
	500 lux	28	78.1	2.4	A				
	250 lux	28	76.4	2.8		B			
	1000 lux	28	74.9	3.0			C		
	2000 lux	28	73.4	3.1				D	
	Background color								
	Blue	16	78.4	2.6	A				
	Green	16	76.7	3.1		B			
	Red	16	76.3	3.2		B			
	Gray	16	75.3	2.7			C		
	Cyan	16	75.1	4.0			C		
	Yellow	16	74.4	2.3				D	
	Purple	16	73.5	3.0					E
Mean text comprehension performance	Illumination color								
	White light	24	7.3	0.59	A				
	Yellow light	24	7.0	0.54	A				
	Illumination intensity								
	500 lux	16	7.5	0.55	A				
	250 lux	16	7.0	0.54		B			
	1000 lux	16	6.9	0.52		B			
	Background color								
	Blue	12	7.5	0.56	A				
	Green	12	7.4	0.42	A	B			
	Red	12	7.1	0.59		B			
	Gray	12	6.7	0.53			C		

Table 3

MANOVA for mean character identification performance and mean text comprehension performance of independent variables.

Experiment	Source	df	SS	MS	*F-value*	*Pr>F* [a]
Mean character identification performance	Gender	1	56.23	56.23	101.84	<0.0001
	Illumination color (L)	1	269.20	269.20	487.55	<0.0001
	Illumination intensity (I)	3	334.81	111.60	202.12	<0.0001
	I*L	3	81.49	27.16	49.19	<0.0001
	Background color (C)	6	250.10	41.68	75.49	<0.0001
	L*C	6	65.41	10.90	19.74	<0.0001
	I*C	18	38.14	2.11	3.84	<0.0001
	I*L*C	18	88.29	4.90	8.88	<0.0001
	Error	55	30.37	0.55		
	Total	111	1214.04			
Mean text comprehension performance	Gender	1	30.24	30.24	1.43	0.2446
	Illumination color (L)	1	111.33	111.33	5.25	0.0314
	Illumination intensity (I)	2	338.29	169.14	7.98	0.0023
	I*L	2	72.64	36.32	1.71	0.2026
	Background color (C)	3	397.92	132.64	6.26	0.0029
	L*C	3	6.61	2.20	0.10	0.9569
	I*C	6	140.83	23.47	1.11	0.3886
	I*L*C	6	44.83	7.47	0.35	0.9012
	Error	23	487.70	21.20		
	Total	47	1630.39			

[a] $p<0.01$ significant level.

Table 4

Different luminance of background color present on the screen.

Background color \ Luminance	40 cd/m^2	Normal
Yellow		
Purple		
Cyan		
Blue		
Green		
Red		

Research Highlights

1. Visual performance was best under white-light, 500 lux, and blue background.
2. The backgrounds with primary colors had better visual performance than the gray background.
3. If the yellow light is necessary, using blue as the background color of will provide better performance.