International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 2, August 2014)

Effects of Illumination Conditions and Chromaticity Contrast on Reading Performance

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***Abstract*—This study investigated the effects of illumination conditions (lighting color and illumination intensity) and chromaticity contrast on reading performance with TFT-LCD screens. Results indicated that the illumination intensity and background color had significant effects on reading performance in experiment 1. In experiment 2, only text color significantly affected reading performance. However, in general, reading performance was higher under white light, 500 lux, and text or background with blue color. According to the results, white light, 500 lux, and text or background with primal colors seemed to be the optimal conditions. If the yellow light is necessary, using blue as the text or background color of will provide better performance.**

***Keywords*—Illumination conditions, Chromaticity contrast, Reading performance.**

I. 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.

Illumination conditions (lighting color and illumination intensity) significantly affect human psychological responses, such as visual performance (Lin, 2005; Lee et al., 2011), color discrimination (Yoshida & Yamamoto, 2003; Tseng et al., 2010) and visual workload (Lin et al., 2008). To support the various purposes of a workplace, the lighting 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. (2008) 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 lighting 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 (Yoshida & Yamamoto, 2003).

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 reading performance using TFT-LCD.

Chromaticity contrast is an important subfactor of color combination and can be an effective way of improving human-computer communication (Lin, 2005; Lin & Huang, 2006; Huang & Chiu, 2007; Huang & Chen, 2008). Though chromaticity contrast can improve visual performance, some chromaticity contrasts may cause added visual problems due to chromatic aberration (Charman, 1991). Further, Buchner and Baumgartner (2007) 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 (Lin, 2005) that significantly affects visual performance (Lin, 2005; Lin & Huang, 2006; Lin, 2003; Chen & Lin, 2004; Lin & Chen, 2006; Lin & Huang, 2009). 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 (Lin, 2005; Lin, 2003).

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 (Buchner and Baumgartner, 2007; Mayr & Buchner, 2010). 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.

In summary, there is a lack of studies concerning the effects of illumination conditions (lighting color and illumination intensity) and chromaticity contrast for reading performance with TFT-LCD.

Therefore, it is important to empirically evaluate the effects of illumination conditions and chromaticity contrast on reading performance.

II. METHODS

2.1 Experimental 1- Colored Background (E1)

2.1.1 Experimental design

The experiment 1 in this study evaluated three independent variables: lighting color, illumination intensity and background color.

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

Three levels of illumination intensity were tested: 250 lux (low-level office illumination), 500 lux (normal office illumination), and 1000 lux (high-level office illumination).

Four background colors were employed, including the three primary colors (red, green and blue) and a center-point one (gray) in the CIE chromaticity coordinates. The four background 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 I show the CIE coordinates (L, x, y) and the RGB code value of the background colors. The text color was gray and with 5 cd/m^2.

Table I
Chromaticity Coordinates Of Background Color

Code / *Color*	CIE(L, x, y)		
	L	x	y
Red	40	6387	3505
Green		2870	5885
Blue		2081	1795
Gray		3305	3337

All subjects completed 24 combinations (2 lighting color × 3 illumination intensity × 4 background color)

2.1.2 Subjects

Twenty students (10 female and 10 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.

2.1.3 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.

2.1.4 Workplace condition

The TFT-LCD was positioned on a table 70 cm in height. The inclination angle of the TFT-LCD screen was 105º (Horikawa, 2001; Sommerich et al., 2001) 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 (Figure 1).

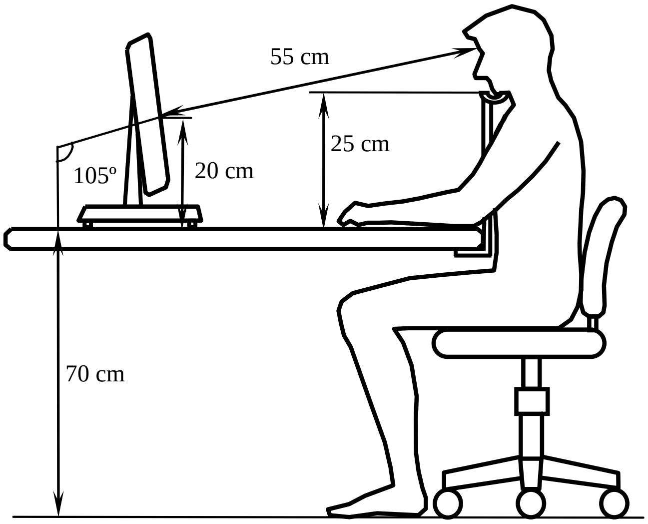

Figure 1. Arrangement of workplace used in the experiment

2.1.5 Task and procedure

Subjects were instructed to perform a 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 147 mm × 183 mm (Figure 2).

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.

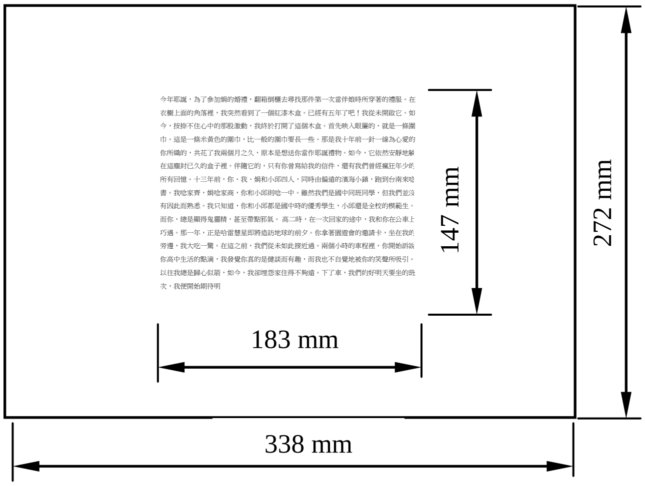

Figure 2. Typical illustration of screen layout of experiment.

2.1.6 Performance measures and data analysis

Reading performance was defined as the number of correct answers of the reading comprehension test. 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 variance (ANOVA) was conducted using Statistical Products & Service Solutions (SPSS 13.0).

2.1.7 Results of experiment 1

The text comprehension performance values under each level of independent variables are shown in Table II. The results of ANOVA for the reading performance of independent variables (Table III) indicates that illumination intensity ($F_{2,23}$ = 7.98, p = 0.002) and background color ($F_{3,23}$ = 6.26, p = 0.003) had significant impact on the reading performance.

Table II
Reading Performance Of Independent Variables And Duncan Grouping Of E1

Independent variable	n	Mean	Duncan grouping		
Lighting color					
White light	24	7.3	A		
Yellow light	24	7.0	A		
Illumination intensity					
500 lux	16	7.5	A		
250 lux	16	7.0		B	
1000 lux	16	6.9		B	
Background color					
Blue	12	7.5	A		
Green	12	7.4	A	B	
Red	12	7.1		B	
Gray	12	6.7			C

Table III
Anova For Reading Performance Of Independent Variables Of E1

Source	df	SS	MS	*F-value*	*Pr>F*
Gender	1	30.24	30.24	1.43	0.245
Lighting color (L)	1	111.33	111.33	5.26	0.031
Illumination intensity (I)	2	338.29	169.14	7.98	0.002
I*L	2	72.64	36.32	1.71	0.203
Background color (C)	3	397.92	132.64	6.26	0.003
L*C	3	6.61	2.20	0.10	0.957
I*C	6	140.83	23.47	1.11	0.389
I*L*C	6	44.83	7.47	0.35	0.901
Error	23	487.70	21.20		
Total	47	1630.39			

Duncan multiple paired-comparisons (Table II) indicated that the reading performance for illumination intensity of 500 lux (7.5) resulted in the highest reading performance, followed by 250 lux (7.0) and 1000 lux (6.9). The blue (7.5) background resulted in the best reading performance, followed by green (7.4), red (7.1) and gray (6.7). The background with the primary colors had better reading performance than the gray. None of the interaction effects of the three independent variables reached a statistically significant level ($p < 0.01$).

2.2 Experimental 2- Colored Text (E2)

The experimental design, experimental apparatus and workplace conditions, task and procedure, and dependent measures and data analysis were the same as those used in experiment 1, except as noted below. In experiment 2, colored text and gray background were employed (Table I).

2.2.1 Subjects

Ten students (5 female, 5 male) who had better reading performance were selected from experiment 1 to serve as subjects for experiment 2.

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

2.2.2 Results of experiment 2

The reading performance under each level of independent variables is shown in Table IV. The results of ANOVA for the reading performance of independent variables (Table V) indicates that only text color ($F_{3,23}$ = 6.37, p = 0.003) had significant impact on the reading performance. None of the interaction effects of the three independent variables reached a statistically significant level ($p < 0.01$).

Table IV
Reading Performance Of Independent Variables And Duncan Grouping Of E2

Independent variable	n	Mean	Duncan grouping		
Lighting color					
White light	24	6.7	A		
Yellow light	24	6.3	A		
Illumination intensity					
500 lux	16	6.7	A		
1000 lux	16	6.5	A		
250 lux	16	6.3	A		
Background color					
Blue	12	7.0	A		
Green	12	6.7	A	B	
Red	12	6.3		B	C
Gray	12	6.1			C

Duncan multiple paired-comparisons (Table IV) indicated that the reading performance for white light (6.7) resulted in better reading performance than yellow light (6.3). Reading performance for illumination intensity of 500 lux (6.7) resulted in the highest reading performance, followed by 1000 lux (6.5) and 250 lux (6.3). The blue (7.0) text resulted in the best reading performance, followed by green (6.7), red (6.3) and gray (6.1).

Table V
Anova For Reading Performance Of Independent Variables Of E2

Source	df	SS	MS	*F-value*	*Pr>F*
Gender	1	1.61	1.61	5.92	0.023
Lighting color (L)	1	1.33	1.33	4.89	0.037
Illumination intensity (I)	2	1.22	0.61	2.24	0.129
I*L	2	1.60	0.80	2.94	0.073
Text color (C)	3	5.21	1.74	6.37	0.003
L*C	3	0.08	0.07	0.10	0.960
I*C	6	0.15	0.02	0.09	0.997
I*L*C	6	0.61	0.10	0.37	0.890
Error	23	6.27	0.27		
Total	47	18.08			

III. DISCUSSION

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

3.1 Lighting Color

Thought the white light resulted in better reading performance than yellow light. But, the ANOVA results showed that lighting color did not significantly affect reading performance. Further, Chung and Lu (2003) 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 significantly affect reading performance in this case. Therefore, white light might be suitable for visual task.

3.2 Illumination Intensity

ANOVA results showed that illumination intensity did significantly affect reading performance in E1. Reading performance 500 lux was better than that under other intensities. For the design of illumination intensity, the American Illumination Engineering Society (1983) suggests that illumination level for general office work should be 750 lux, while the German DIN is 500 lux.

These results are consistent with results obtained by previous studies (Lee et al., 2011; Lin & Huang, 2009; Chung & Lu, 2003; Kubo et al., 2000) that illumination intensity did affect significantly visual performance.

First, the screen luminance of a given TFT-LCD is affected by illumination intensity (Lin & Huang, 2009; Chung & Lu, 2003), so high illumination intensity may cause screen images to fade due to screen brightness (Hori & Kondo, 1993). Second, the actual luminance contrast ratio percentage decreased with increasing illumination intensity (Kubo et al., 2000) because of surface reflection. With higher illumination intensity, there was a greater percentage decrease in luminance contrast (Lin & Huang, 2009). These two reasons may explain why the subjects had better reading performance at 500 lux than at 1000 lux.

However, compared with 500 lux, 250 lux was not associated with better reading 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 (Isensee & Bennett, 1983). Second, the low-level illumination intensity may cause more visual fatigue than normal illumination intensity, thus decreasing reading performance.

3.3 Chromaticity Contrast

ANOVA results showed that chromaticity contrast did significantly affect reading performance. Text or background with blue color resulted in best reading performance. Overall, the primary colors (blue, green, and red) seemed to promote better reading performance than gray. This result is consistent with the findings of Lin and Huang (2009) that the primary colors had better perception time. With reduced of color saturation, the blue primary is more visible than red or green (Langendijk, & Heynderickx, 2003). Thus subjects were more able to accept a decreased saturation for the blue primary than for the other two primaries. In summary, text or background with primary colors had better reading performance than monochromatic text or background.

3.4 Interaction Effects

Thought the interaction effects of the three independent variables all did not reached statistically significant levels.

However, white light, 500 lux and blue text resulted in the best reading performance (7.7). Yellow light, 250 lux and gray text; and yellow light, 1000 lux and gray text resulted in the worst reading performance (5.9).

3.5 Difference between E1 and E2

Illumination intensity and background color had significant impact on the reading performance in E1. But, only text color had significant impact on the reading performance in E2. Further, the sum square (SS) error of E2 was significantly less than E1. These differences might due to the subjects of E2 who had more experience as they participate in E1 and had better reading performance.

IV. CONCLUSION

For the current TFT-LCD, our results imply that under equivalent and low screen luminance conditions, white light, 500 lux illumination, and text or background with blue color were the better conditions in an office setting. 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 text or background color.

Acknowledgements

This study was supported by a research grant from the National Science Council of the Republic of China, grant no. NSC 97-2221-E-168-029.

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