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Effects of Lighting Color, Illumination Intensity, and Text Color on Visual Performance

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Abstract: This study investigated the effects of lighting color, illumination intensity, and text color on visual performance. Experiment 1 conducted character identifying test and Experiment 2 conducted reading comprehension test. Results of experiment 1 indicated that all the three independent variables had significant effects on mean percentage of character identification. Mean percentage was best under white light (67.05%), 500 lux (69.85%), and blue text (69.22%). Results of experiment 2 indicated that the lighting color and text color had significant effects on mean answer for reading comprehension. Mean answer were higher under white light (6.68) and blue text (6.97). In general, the texts with primary colors had better mean percentage and mean answer than the gray. According to the results, white light, normal ambient illumination and a text with primal colors seemed to be the optimal conditions. If the yellow light is necessary, using blue text will provide better visual performance than gray text. Further, the Pearson product-moment correlation coefficient indicated that short-term visual task measurement might be suitable to evaluate the visual performance.

Keywords: Lighting color; illumination intensity; text color; visual performance.

1. Introduction

Lighting color usually significantly affect human psychological responses, such as visual performance [1], color discrimination [2, 3] and visual workload [4]. To support the various purposes of a workplace, the lighting colors 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. [4] reported that both visual acuity and subjective visual fatigue were significantly affected by the lighting color. But there are insufficient studies on the effects of lighting color on visual performance.

Illumination intensity is an important consideration in workstation design [5]. In addition to the effects of illumination intensity on screen luminance, the surface-reflected light also affects the chromaticity coordinates of colors [2]. Furthermore, under usual illumination conditions for working with a 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.

Chromaticity contrast (text color) is an important subfactor of color combination and can be an effective way of improving human-computer communication [1, 5, 6]. Though chromaticity

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contrast can improve visual performance, some color combinations may cause added visual problems due to chromatic aberration [7].

In summary, there is a lack of studies concerning the effects of lighting color, illumination intensity, and text color for both short-term and long-term visual tasks. Therefore, it is important to empirically evaluate the effects of lighting color, illumination intensity, and text color on visual performance.

2. Experiment 1: short-term visual task

2.1. Experimental design

The experiments in this study evaluated three independent variables: lighting color, illumination intensity, and text 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 text 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 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) of the text and background colors.

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

Color \ Code		CIE(L, x, y)		
		L	x	y
Text	Red	5	6387	3505
	Green		2870	5885
	Blue		2081	1795
	Gray		3305	3337
Background	Gray	40	3301	3340

2.2. 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.

All subjects completed 24 treatments (2 lighting color × 3 illumination intensity × 4 text 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 [8, 9]. The inclination angle of the TFT-LCD screen was 105º [10] 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 [11] 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 2.5 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 percentage (mean of correct character identification percentage) for all of the 10 female and the 10 male subjects together were used instead of individual character identification performance to avoid the confounding of subjects' difference. Analysis of variance (ANOVA) and calculation of effect size (η^2) [12, 13] were conducted using Statistical Products & Service Solutions (SPSS 13.0).

2.7. Results of experiment 1

The mean percentages under each level of independent variables are shown in Table 2. The results of ANOVA for the mean percentage of independent variables (Table 3) indicated that all main effects, namely lighting color ($F_{1,23}$ = 31.25, p < 0.001), illumination intensity ($F_{2,23}$ = 232.80, p < 0.001) and text color ($F_{3,23}$ = 97.35, p < 0.001) all had significant impact on the mean percentage. Further, the effect size showed that illumination intensity (η^2 = 0.33) had the most significant impact on the mean percentage, followed by text color (η^2 = 0.21), and lighting color (η^2 = 0.02).

Duncan multiple paired-comparisons (Table 2) indicated out that the mean percentage for white light (67.05%) was significantly greater than that for yellow light (65.77%). For illumination intensity, 500 lux (69.85%) resulted in the best mean percentage, followed by 250 lux (65.29%), and 1000 lux (64.10%). For text color, blue (69.22%) text resulted in best mean percentage, followed by green (67.18%), red (65.11%), and gray (64.14%). Generally, primary colors text provided better mean percentage than gray text.

Interaction effects of the three independent variables, only lighting color × illumination intensity ($F_{2,23}$ = 8.63, p = 0.002) and illumination intensity × text color ($F_{6,23}$ = 3.42, p = 0.015) reached statistically significant levels (Table 3). White light and 500 lux resulted in the best mean percentage (70.40%) and yellow-light and 1000 lux resulted in the worst mean percentage (64.00%); blue text under 500 lux resulted in the best mean percentage (73.67%) and gray text under 1000 lux resulted in the worst mean percentage (61.47%). Overall, white light, 500 lux and blue text resulted in the best mean percentage (74.08%); yellow light, 1000 lux and gray text resulted in the worst mean percentage (61.24%).

Table 2. Mean percentage and mean answer for each level of independent variables and duncan grouping

Experiment	Independent variable	n	Mean	Duncan grouping				
Mean percentage (character identification performance)	Illumination color							
	White light	24	67.05		A			
	Yellow light	24	65.77			B		
	Illumination intensity							
	500 lux	16	69.85		A			
	250 lux	16	65.29			B		
	1000 lux	16	64.10				C	
	Background color							
	Blue	12	69.22		A			
	Green	12	67.18			B		
	Red	12	65.11				C	
	Gray	12	64.14					D

Mean answer (text reading comprehension performance)	Illumination color							
	White light	24	6.68		A			
	Yellow light	24	6.34			B		
	Illumination intensity							
	500 lux	16	6.69		A			
	1000 lux	16	6.54		A			
	250 lux	16	6.30		A			
	Background color							
	Blue	12	6.97		A			
	Green	12	6.67		A	B		
	Red	12	6.27			B	C	
	Gray	12	6.13				C	

Table 3. ANOVA for mean percentage and mean answer for each level of independent variables

Experiment	Source	df	SS	MS	*F-value*	*Pr>F* [a]
Mean character identification	Gender	1	358.45	358.45	567.08	<0.001
	Lighting color (L)	1	19.75	19.75	31.25	<0.001
	Illumination intensity (I)	2	294.30	147.15	232.80	<0.001
	L* I	2	10.92	5.46	8.63	0.002
	Text color (C)	3	184.61	61.54	97.35	<0.001
	L*C	3	0.13	0.04	0.07	0.976
	I*C	6	12.97	2.16	3.42	0.015
	L*I* C	6	1.57	0.26	0.41	0.862
	Error	23	14.54	0.63		
	Total	47	897.24			
Mean text comprehension	Gender	1	1.613	1.613	5.920	0.023
	Lighting color (L)	1	1.333	1.333	4.892	0.037
	Illumination intensity (I)	2	1.222	0.611	2.242	0.129
	L* I	2	1.602	0.801	2.939	0.073
	Text color (C)	3	5.21	1.737	6.374	0.003
	L*C	3	0.080	0.027	0.098	0.960
	I*C	6	0.145	0.024	0.089	0.997
	L*I* C	6	0.605	0.101	0.370	0.890
	Error	23	6.267	0.272		
	Total	47	18.077			

[a] $p<0.05$ significant level.

3. Experiment 2: long-term visual task

3.1. Method

The experimental design, experimental apparatus and workplace conditions were the same as those used in experiment 1.

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

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). All subjects completed 24 treatments (2 lighting color × 3 illumination intensity × 4 text color). Articles were assigned randomly for the 24 treatments of each subject.

The articles were presented in Chinese. These articles were selected from various e-books including romance, science fiction, fiction, and historical stories. 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.

The subjects were required to read the article and then in 10 min complete a 10-question comprehension test, in which, each question included 4 options, with only one correct), at the end of the experimental session. The 10 questions are produced from the corresponding article. 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. The overall experiment lasted about 24 hr for each subject, including regular breaks to reduce fatigue. 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 5 female and 5 male subjects were used instead of individual number of correct answers to avoid the confounding of subjects’ difference. Analysis of variance (ANOVA) and calculation of effect size (η^2) were conducted using Statistical Products & Service Solutions (SPSS 13.0).

3.4. Results of experiment 2

The mean answers under each level of independent variables are shown in Table 2. The results of ANOVA for the mean answer of independent variables (Table 3) indicates that only lighting color ($F_{1,23} = 4.892$, $p = 0.037$) and text color ($F_{3,23} = 6.374$, $p = 0.003$) had significant impact on the mean answer.

Duncan multiple paired-comparisons (Table 2) indicated that the mean answer for white light (6.68) resulted in better mean answer than yellow light (6.34). The blue (6.97) text resulted in the best mean answer, followed by green (6.67), red (6.27) and gray (6.13). Again, the text with the primary colors all had better mean answer than the gray text.

Interaction effects of the three independent variables all did not reached statistically significant levels (Table 3). However, white light, 500 lux and blue text resulted in the best mean answer (7.7). Yellow light, 250 lux and gray text; and yellow light, 1000 lux and gray text resulted in the worst mean answer (5.9).

4. Discussion

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

4.1. Lighting color

The ANOVA results showed that lighting color did significantly affect visual performance (mean percentage and mean answer). White light resulted in better visual performance than yellow light. Three reasons may be offered. First, because the lighting color slightly shifted the color coordinates (x, y) of text colors. Second, the subjects were more accustomed to the white light than yellow light condition because white light is the more common lighting color for general offices. Third, Chung and Pease [14] showed that the pupil size is larger under yellow light than with luminance-matched white light. Enlarged pupils over a long period might increase eye fatigue and then reduce visual performance.

4.2. Illumination intensity

ANOVA results showed that illumination intensity did significantly affect mean percentage. Mean percentage under 500 lux was better than that under other illumination intensities. For the design of illumination intensity, the American Illumination Engineering Society [15] suggests that illumination level for general office work should be 750 lux, while the German DIN is 500 lux. These results are consistent with Läubli et al. [16] and Stammerjohn et al. [17], who found that most offices are around the range of 500 lux and they are also consistent with results obtained by previous studies [14, 18, 19] that illumination intensity did significantly affect visual performance. First, the screen luminance of a given TFT-LCD is affected by illumination intensity [14, 18, 20], so high illumination intensity may cause screen images to fade due to screen brightness [21]. Second, the actual luminance contrast ratio percentage decreased with increasing illumination intensity [19] because of surface reflection. With higher illumination intensity, there was a greater percentage decrease in luminance contrast [18]. These two reasons may explain why the subjects had better mean percentage at 500 lux than at 1000 lux.

Further, compared with 500 lux, 250 lux was not associated with better mean percentage. 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 mean 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 the500 lux might result in slightly greater direct reflected light than 250 lux [22]. Second, the 250 lux may cause more visual fatigue than 500 lux, thus decreasing mean percentage.

Illumination intensity did not significantly affect mean answer. This result was inconsistent with result obtained by previous study [23]. This might be due to the reversed of text and background colors. Further, the result was also inconsistent with experiment 1 that illumination intensity did significantly affect mean percentage. This might be due to the Hawthorne effect and extra paid for each correct answer.

4.3. Text color

ANOVA results showed that text color did significantly affect visual performance (mean percentage and mean answer). Blue text resulted in best visual performance, followed by green, red, and gray. Overall, the color text seemed to promote better visual performance than the gray text. This result is consistent with the findings of Lin and Huang [18] that the primary colors had better perception time and can improve visual performance. Lippert [24] proposed that the ΔE scale could provide good prediction of legibility performance. Since the ΔE scales are smaller for the gray than for the primary colors under the same luminance, their lower small ΔE also resulted in worse visual performance. In summary, chromatic text with primary colors had better visual performance than monochromatic text.

4.4. Interaction effects

Though the interaction effects of the three independent variables only lighting color × illumination intensity and illumination intensity × text color reached statistically significant levels in mean percentage (Table 3), the effect size showed that the interaction effects of the three independent variables are very slight. The effect size of lighting color × illumination intensity and illumination intensity × text color was only 0.012 and 0.015, respectively. Despite the small effect size of the interaction effects, compared to white light, the yellow light had largest decrease in mean percentage under 250 lux than other illumination intensity (Figure 1). In other words, the effect of lighting color is greater under low illumination intensity than under high illumination intensity.

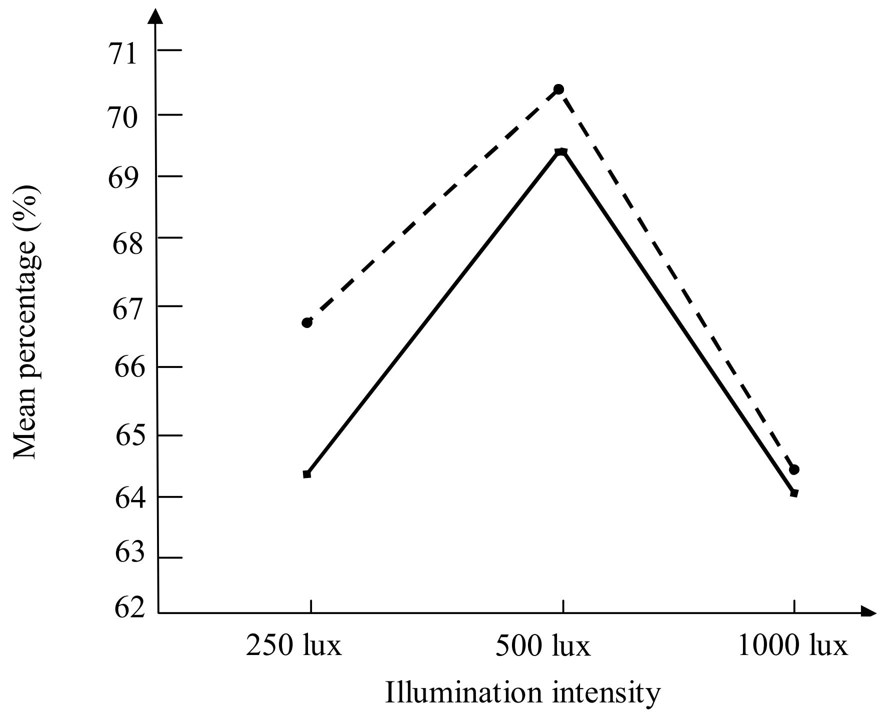

Figure 1. Interaction effect of lighting color × illumination intensity for mean percentage. Yellow-light: ———— ; White-light: – – – – –

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

The Pearson product-moment correlation coefficient ($r = 0.535$, $p < 0.001$) indicated that short-term performance (mean percentage) was significantly related to long-term performance (mean answer). 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

Our results imply that under equivalent and low screen luminance conditions, white light, 500 lux and color text were the better visual task setting conditions. Further, the effect size shows that the illumination intensity has the greatest impact on short-term visual tasks and text 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 text color.

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References

[1] Lin, C. C. 2005. Effects of screen luminance combination and text color on visual performance with TFT-LCD. *International Journal of Industrial Ergonomics*, 35: 229-235.

[2] Yoshida, Y. and Yamamoto, Y. 2003. Color management of liquid crystal display placed under light environment, Electronics and Communications, in: Japan 86(7) 2003. *Translated from Denshi Joho Tsushin Gakkai Ronbunshi 2002*, J85-A (7): (2002) 793-805.

[3] Tseng, F. Y., Chao, C. J., Feng, W. Y., and Hwang, S. L. 2010. Assessment of human color discrimination base on illuminant color, ambient illumination and screen background color for visual display terminal workers. *Industrial Health*, 48: 438-446.

[4] Lin, C. J., Feng, W. Y., Chao, C. J., and Tseng, F. Y. 2008. Effects of VDT workstation lighting conditions on operator visual workload. *Industrial Health*, 46: 105-111.

[5] Lin, C. C. and Huang, K. C. 2006. Effects of ambient illumination and screen luminance combination on the character identification performance of desktop TFT-LCD monitors. *International Journal of Industrial Ergonomics*, 36: 211-218.

[6] Huang, K. C. and Chiu, T. L. 2007. Visual search performance on an LCD monitor: effects of color combination of figure and line width of icon border. *Perceptual and Motor Skills*, 104: 562-574.

[7] Charman, W. N. 1991. Limits on visual performance set by the eye's optic and the retinal cone mosaic, in: J. J. Kulikowski, V. Walsh, I. J. Murray (Eds.). Vision and visual dysfunction: *Limits of Vision*, 5: 81-96.

[8] Burgess-Limerick, R., Mon-Willams, M., and Coppard, V. L. 2000. Visual display height. *Human Factors*, 42: 140-150.

[9] Horikawa, M. 2001. Effect of visual display terminal height on the trapezius muscle hardness: Quantitative evaluation by a newly developed muscle hardness meter. *Applied Ergonomics*, 32: 473-478.
[10] Sommerich, C. M., Joines, S. M. B., and Psihogios, J. P. 2001. Effects of computer monitor viewing angle and related factors on strain, performance, and preference outcomes. *Human Factors*, 43: 39-55.
[11] Fukuda, T. 1992. Visual capability to receive character information part I: How many characters can we recognize at a glance. *Ergonomics*, 35: 617-627.
[12] Kirk, R. E. 1982. *Experimental design: Procedures for the behavioral sciences*. CA: Brooks/Cole, 2nd ed., Belmont.
[13] Tabachnick, B. G. and Fidell, L. S. 1989. "*Using multivariate statistics*". New York: Harper & Row, 2nd ed.
[14] Chung, H. H. and Lu, S. 2003. Contrast-ratio analysis of sunlight-readable color LCDs for outdoor applications. *Journal of the Society for Information Display*, 11: 237-242.
[15] American National Standards Institute, Illuminating Engineering Society of North America, American National Standard Practice for Industrial Lighting. ANSI/IES RP-7, 1983.
[16] Läubli, Th., Hünting, W., and Grandjean, E. 1982. Visual impairments in VDU operators related to environmental conditions, in: E. Grandjean, E. Vigliani (Eds.). *Ergonomics Aspects of Visual Display Terminals*, Taylor & Francis, London.
[17] Stammerjohn, L. W., Smith, M. J., and Cohen, B. G. F. 1981. Evaluation og work station design factors in VDT operators. *Human Factors*, 23: 401-412.
[18] Lin, C. C. and Huang, K. C. 2009. Effects of color combination and ambient illumination on visual perception with TFT-LCD. *Perceptual and Motor Skills*, 109: 1-19.
[19] Kubo, M., Uchi, T., Narutaki, Y., Shinomiya, T., and Ishii, Y. 2000. Development of "Advanced TFT-LCD" with good legibility under any ambient light intensity. *Journal of the Society for Information Display*, 8: 299-304.
[20] Hori, H. and Kondo, J. 1993. Contrast ratio for transmissive-type TFT-addressed LCDs under ambient-light. *Journal of the Society for Information Display*, 1: 325-327.
[21] Ostberg, O. 1980. "*Accommodation and visual fatigue in display work*". in: E. Grandjean and E. Vigliani (Eds.), Ergonomics Aspects of Visual Display Terminals, Taylor and Franics, London.
[22] Isensee, S. H. and Bennett, C. A. 1983. The perception of flicker and glare on computer CRT. *Display*, 25: 177-184.
[23] Lin, C. C. and Huang, K. C. 2013. Effects of ambient illumination conditions and background color on visual performance with TFT-LCD screens. *Displays*, 34: 276-282.
[24] Lippert, T. M. 1986. Color-difference prediction of legibility performance for CRT raster imagery. *SID Digest of Technical Papers*, 16: 86-89.