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Original Article

Assessment of Human Color Discrimination Based on Illuminant Color, Ambient Illumination and Screen Background Color for Visual Display Terminal Workers

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Abstract: Human performance on color discrimination in visual display terminals may be affected by illuminant colors, the level of ambient illumination and background colors of the monitor. Few studies have focused on this topic. This study investigated human color discrimination ability in a simulated control room. Ten subjects were recruited as participants to perform a series of experimental tasks. A complete factorial (2 × 3 × 3) within-subject design was used. The independent variables were three illuminant colors (red, blue, and white), two ambient illumination levels (50 lux and 300 lux), and three background colors (black, blue and brown); the three dependent variables were the color discrimination ability (error scores), completion time and subject preference. The results showed that the illuminant colors and the screen background colors both significantly influenced human color discrimination ability (*p*<0.01). The result of this research can be used in control room design when considering the effect of color.

Key words: Illuminant color, Ambient illumination, Screen background color, Color discrimination, Visual display terminal

Introduction

Human reliance on computers to execute job-related tasks has increased immensely with advances in computer technology[1,2]. These kinds of tasks were once performed through a man-machine interface (MMI) by using traditional hardware equipment such as meters, dials and monochrome televisions. However, as computers have replaced MMI, the tasks have changed, in both their uses of time and scope, and an integrated display has entered the mainstream.

Today, the visual display terminal (VDT) is believed to be the most convenient tool for human/computer interface in industrial environments. Operators control and monitor a complex system through the computer user interfaces of keyboards, mice or touch screens. Research has identified the use of computers at work as a contribution factor for occupational stress[3]. Nevertheless, in order to acquire information rapidly and accurately, humans who use computers at work must suffer more stress than using traditional hardware in MMI. Hence, the design of smooth communications between human and computer is extremely important.

One application of computers that is growing rapidly is performing military maneuvers in defense industries[4]. Computerized systems integrate military information from various sources of the battlefield[5–8], but the real information translated into a conceptual representative (e.g., text or symbols) creates a battlefield situation presented on the VDTs that lacks a sense of reality. Humans want to operate with a high level of situation awareness, and they will rely more on well-designed system aids for critical decision-making. This makes

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the interface of the computer-based controlling system one of the most important factors for improving the defense industry's task of preventing safety-related accidents[9].

Common symbology is the basis of military information-sharing during military deployment or fighting. Computerized chain of command system that combines Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C^4ISR) is an important issue in defense industries. The most important function of the C^4ISR interface is to integrate all kinds of information retrieval, then to translate that information into a common and meaningful symbol for real-time feedback to all users[10]. To avoid misunderstanding symbols, which may result in casualties on the battlefield, the symbology of the computer-based interface must be unanimous, adequate and identifiable.

Despite this, many systems have been developed with different symbology to represent common types of data. With the requirement for integrating each of the systems with uniform symbology, it is necessary to standardize this symbology for joint operations through the C^4ISR process by developing a standard which all users can understand. Thus, the warrior symbology, "Military Standard 2525b" was produced[11]. An example of the simulated radar picture which included symbols for MIL-STD 2525b was shown in Fig. 1.

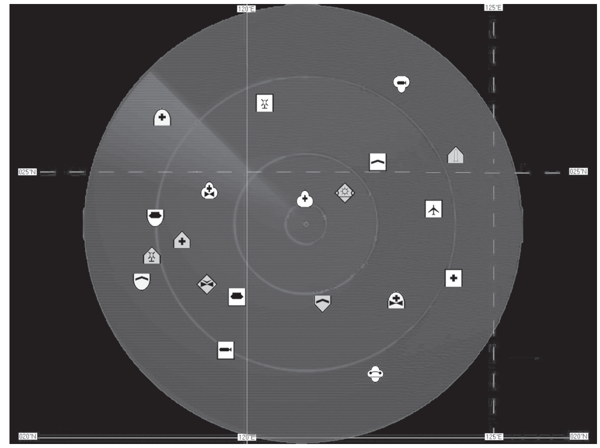

Fig. 1. An example of the simulated radar picture included symbols for MIL-STD 2525b.
Users can plot the locations of all troops in a given region on a military operations planning map, or add the nearby locations of potential threats.

Although the standardized warrior symbology regulates most basic principles, including shape and color of symbols, there are other potential problems. For example, in the control rooms of some military battlefield control towers, operators manipulate a radar system under red or blue illuminant, and operators working in the information center or main machine control room of military ships perform sonar detection tasks on the VDTs under red, blue, and white illuminant[12]. In this kind of environments, any hue discrimination errors are critical. Therefore, the duration of working time can not exceed four hours at one time. However, variations in room illuminant and illumination can completely change the emergent rating of combat readiness, and illumination or color illuminant factors may also seriously influence the human perception ability to discriminate symbology. When symbols are used, illumination or illuminant color might lead to serious safety accidents or human error unless careful consideration is given to the design of the user interface[13]. Lin *et al.*[14] indicated that illuminant color has a significant effect on visual acuity, and any changes to illuminant color in the workplace should consider its effect on human psychology and physiology. In occupational work, poor visual discrimination is work-task-specific and can be aggravated when exposure to the task is prolonged. Noticeability, the interaction between VDT task performance and environmental illuminant, also becomes an essential issue in these applications.

The background color of the screen is another important factor in visual detection that could affect performance on VDT work. The standardized warrior symbology does not regulate the background color either. This might arise some unexpected problems in human's visual performance. For instance, previous research had indicated that text/background color combinations also significantly influence visual performance and subjective preference[2, 15, 16]. Appropriate text/background color combinations of a VDT interface could be an effective means by which to improve visual performance with regard to searching speed and legibility, and the luminance contrast between text and background colors is an important factor in color combination[17]. In several of the warrior symbology detection tasks that were surveyed in the information center or control room, the greater part of background colors were formed by brown (which represents the land on chromatic screen), blue (which represents the sea on chromatic screen) and black (which means both of land and sea on monochrome screen). In foregoing situation, the main reason that the ambient illumination is very low. Currently, few researches have been done regarding the effects of target/background color combinations on visual performance under different illuminant colors.

The objective of this study was to examine the influence of different levels of illumination, colors of illuminant and background colors on discrimination performance in combat symbology on VDTs. A lab experiment was conducted to explore the visual discrimination, and the result may provide design guidelines for designing effective signals to reduce or eliminate human errors of VDT operators.

Method

Subjects

The subjects were 10 volunteers (4 men and 6 women) who were paid for their participation in this study. Their ages ranged from 20 to 31 yr (M=26.1 yr, SD=3.18). All subjects had a corrected visual acuity of 0.8 or better, as well as normal color vision. The protocol of this experimental study has been approved by the Research Ethics Committee of National Chung-Shan Institute of Science and Technology. Each subject signed a letter of consent before the experiment. In the beginning of each treatment, the subjects adapted to the ambient illumination for 20 min before starting. The subjects were randomly assigned to each treatment and test individually and were also instructed to avoid VDT work for at least 3 h prior to the experiment.

Apparatus

A Topcon-acp.8 vision tester was used to test the visual acuity of each subject. Another instrument of Optec 2000 tester which can show six Ishihara plates was used to test all subjects' color vision[18, 19]. An Intel Pentium 4 desktop computer with an Advantech Fpm-3175tvr-t 17-inch color Liquid Crystal Display (LCD) monitor with a display resolution of 1,280 × 800 pixels at a refresh rate of 60 Hz was used. The monitor was calibrated with a Minolta CS-100 chroma meter. A chin rest restrained the subject's head position, ensuring a constant viewing distance of 50 cm. Before the experiments began, the monitor was warmed up for 2 h.

A test program was developed in accordance with the theorem of the Farnsworth-Munsell 100 (FM-100) hue test[20]. Kinnear and Sahraie[21] employed the FM-100 hue test norms of normal observers for each year of age 5–22 and decades 30–70. Bernard and John[22] used the FM-100 hue test measurement to evaluate the discrimination of colors, and Murray *et al*.[23] employed the simulated Munsell samples on the screen to study the changes of the color appearance under low illumination. In the current study, the color-matching test that follows the FM-100 hue test principles was used. The experiments were conducted in a darkened room, and subjects performed a color-matching task under different color illuminant sources. Environmental illuminant with a diffuse light source from a fluorescent tube simulated the normal and combat situations in the control room or information center. The Commission International de l'Eclairage (CIE; International Commission on Illumination) primaries value and illumination of environmental illuminant were measured with a Minolta CL-200 chroma meter at the height of the keyboard, and the background colors of LCD screen, simulated Munsell caps were measured with a Minolta chroma meter CS-100. The CIE chromaticity diagram of the simulated Munsell caps, background colors and illuminant colors were shown in Fig. 2.

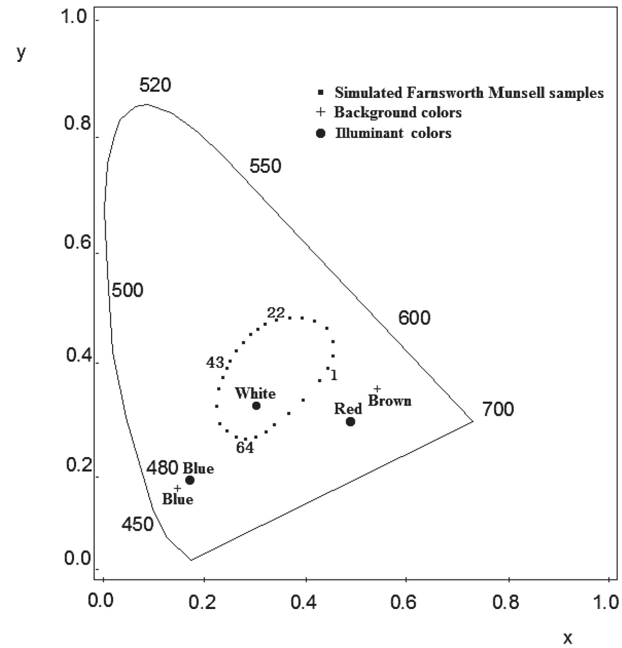

Fig. 2. Chromaticity coordinates of the colors were used in the 85 simulated Farnsworth Munsell samples, screen background colors and illuminant colors.

Experimental design

The study used a complete factorial (2 × 3 × 3) within-subject design. The independent variables were two ambient illumination levels (50 lux and 300 lux), three illuminant colors (red, blue, and white), and three background colors (black, blue and brown). The three dependent variables were the error scores, completion time, and the subjective preference. The CIE chromaticity coordinates (x, y) of the three illuminant colors are presented in Table 1, the chromaticity coordinates and luminance values of background colors are shown in Table 2 and the CIELuv space of the simulated Munsell caps are presented in Table 3. Each subject executed eighteen (2 × 3 × 3) experimental tasks at random under different setting conditions.

Task and procedure

The test program was developed in accordance with the theorem of the FM-100 hue test, which was designed to measure zones of color confusion and

Table 1. The CIE chromaticity coordinates (x, y) of the illuminant colors

Illuminant colors	x	y	z
White	0.32	0.35	0.33
Red	0.55	0.28	0.17
Blue	0.17	0.19	0.64

Table 2. The CIE chromaticity coordinates (x, y) for screen the background colors of screen

background colors	x	y	L
Black	0.28	0.35	0.48
Blue	0.16	0.16	5.3
Brown	0.57	0.35	3.5

L = luminance (cd/m^2).

separates normal trichromats into classes of outstanding, average, and inferior color discrimination. The color-matching test that follows the FM-100 principles, which contains 85 specific of colors and is divided into four groups (1 group of 22 and 3 groups of 21 colors), with each group representing a different series of just noticeably different shades of colors, e.g., from yellow to green when the colors are arranged in proper order. The experiment interface is shown in Fig. 3. Two colors are repeated and fixed as pilot colors at either end of one group, representing the correct colors and serving as judgmental anchor points. Before the experiment, the groups and colors were arranged in a pre-determined random order, and the subjects could practice operating the interface before each test. The object of the experiment was to arrange the colors in order according to different shades of colors, and the subject's task was to arrange the colors into the appropriate sequence between each pair of anchor points on the screen. Each color was assigned a number in the program in order to facilitate scoring, but the numbers were not visible to the subjects. The error score for individual caps was calculated based on Kinnear and Sahraie's[21] method where the magnitude of difference between the cap and the two adjacent caps is summed and then 2 is subtracted from the error score to scale the value so that a perfect arrangement has an error score of 0. The score for each row and total were then calculated from the sum of the individual cap values.

At the end of the experiment, subjects completed the post-experiment questionnaire regarding the participant's opinion about the workload under different illuminant colors, ambient illumination levels and background colors. The questionnaire was based on the National Aeronautics and Space Administration-Task Load Index (NASA-TLX), which was one of the most widely known and widely used tools for assessing subjective workload[24]. The NASA-TLX is in two-parts. In the first part, the subjects evaluate the contribution of six factors (Mental, Physical, and Temporal demands and Performance, Effort, and Frustration levels) to the workload of the task, choosing the more important factor in 15 paired comparisons. Second, the subject estimates workload by providing numerical ratings for each of the six scales, which reflects the magnitude of the experimental task. Each scale is presented as a 100-mm line with "low" and "high" marked in five scales. The sixth scale, the "performance" scale, extends from "good" to "poor". Subjects mark a X on the 100-mm line, and the position of signal translates into a score (between 0 and 100). The overall workload score is calculated by multiplying each raw rating given by the subject. The sum of the weighted ratings is then divided by 15 (the sum of the weights) to give an absolute workload score that lies between 0 and 100.

Results

The mean proportion of completion time, error scores and subjective preference under each level of the independent variables is shown in Table 4. The basic design independent variables were tested by the repeated measures analysis of variance (ANOVA), and these results are summarized in Table 5.

Error scores

Table 5 shows the ANOVA results of error scores. The results indicated that the main effects of illuminant colors and screen background colors were significant. The result of ANOVA for the error scores showed that the effect of ambient illumination levels was not statistically significant. The result demonstrated that the illuminant colors and background colors on the screen influenced subjects' color discrimination performance. Further analyses of illuminant colors and screen background colors indicated a significant simple main effect on the error scores; the result of the Duncan grouping test showed that the error scores under white illuminant was significantly lower than the error scores under red or blue illuminant. On the other hand, the Duncan grouping test result demonstrated that the best color discrimination occurred under black and brown background colors, followed by brown and blue background colors.

Figures 4 and 5 show the results for the significant effects. In Fig. 4, the comparison of performance of illuminant colors, the white illuminant performed better than red or blue illuminant. As shown in Fig. 5, a black background color resulted in fewer errors than did a blue or brown background. Results were very consis-

Table 3. The CIELuv space of the simulated FM-100 caps

	Group1																					
N	85	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
u'	0.259	0.261	0.263	0.267	0.265	0.264	0.262	0.259	0.258	0.256	0.253	0.246	0.243	0.240	0.235	0.227	0.225	0.215	0.210	0.210	0.207	0.204
v'	0.508	0.511	0.515	0.518	0.522	0.523	0.526	0.528	0.530	0.533	0.535	0.534	0.535	0.536	0.538	0.538	0.535	0.538	0.536	0.533	0.532	0.530
ΔE		6.062	6.704	6.538	5.749	2.916	4.466	4.792	2.848	5.133	4.675	10.258	4.259	3.480	8.325	11.757	5.670	14.767	7.174	4.710	4.862	5.513
	AverageΔE: 6.22																					
L	Average luminance: 65.9 (cd/m^2), Range from 62.8–73.3 (cd/m^2)																					
	Group2																					
N	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
u'	0.203	0.198	0.194	0.191	0.189	0.187	0.184	0.181	0.178	0.176	0.174	0.172	0.170	0.166	0.165	0.163	0.162	0.161	0.156	0.156	0.155	
v'	0.530	0.528	0.526	0.525	0.524	0.523	0.523	0.522	0.520	0.520	0.518	0.516	0.516	0.513	0.511	0.509	0.508	0.507	0.504	0.501	0.499	
ΔE		8.851	5.675	3.990	3.156	3.153	5.049	3.969	4.792	3.137	3.887	3.088	3.136	6.945	3.483	3.915	1.751	1.754	8.610	4.746	3.548	
	AverageΔE: 4.33																					
L	Average luminance: 69.8 (cd/m^2), Range from 67.3–74.5 (cd/m^2)																					
	Group3																					
N	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	
u'	0.154	0.152	0.151	0.150	0.150	0.151	0.151	0.146	0.147	0.149	0.150	0.152	0.154	0.156	0.160	0.164	0.165	0.159	0.168	0.170	0.172	
v'	0.497	0.496	0.494	0.492	0.490	0.484	0.479	0.475	0.469	0.463	0.458	0.453	0.448	0.445	0.438	0.432	0.430	0.428	0.428	0.426	0.425	
ΔE		2.409	2.680	2.687	3.645	8.345	6.406	8.102	7.871	8.830	6.650	6.087	6.949	4.429	9.346	9.488	1.674	7.585	10.568	3.613	2.199	
	AverageΔE: 5.98																					
L	Average luminance: 68.2 (cd/m^2), Range from 65.3–73.0 (cd/m^2)																					
	Group4																					
N	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
u'	0.177	0.181	0.185	0.188	0.193	0.199	0.201	0.206	0.211	0.218	0.221	0.224	0.230	0.233	0.237	0.241	0.242	0.249	0.253	0.254	0.252	
v'	0.425	0.424	0.423	0.421	0.424	0.427	0.427	0.432	0.436	0.439	0.447	0.451	0.457	0.462	0.468	0.473	0.479	0.485	0.490	0.494	0.503	
ΔE		5.191	5.469	3.716	6.896	6.918	2.788	7.767	7.703	8.814	9.881	6.210	10.346	8.073	8.986	7.784	7.646	12.639	8.786	5.618	11.985	
	AverageΔE: 7.66																					
L	Average luminance: 64.0 (cd/m^2), Range from 62.3–72.6 (cd/m^2)																					

N = the cap numbers, ΔE = the color difference between two adjacent colors, L = luminance (cd/m^2).

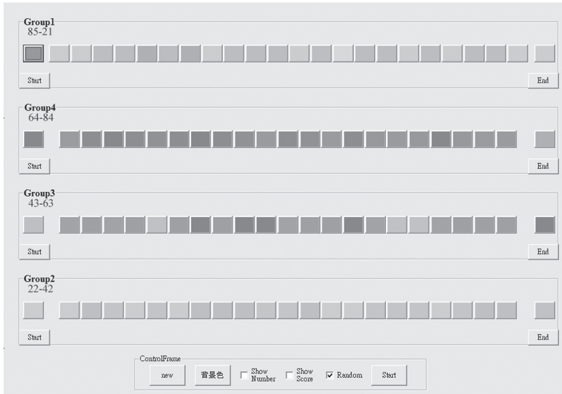

Fig. 3. The simulated Munsell samples interface was used in a successive color-matching task.
The gray background replaced by the black, blue and brown backgrounds in the experiment.

tent over the entire color range of the FM-100 hue test.

Completion time

Table 5 shows the ANOVA results of completion time. The results indicated that the main effects of ambient illumination were significant. However, the ANOVA results for completion time showed that the differences in main effects of illuminant colors and screen background colors levels were not statistically significant. Fig. 6 showed the results for the significant effects of ambient illumination. The result of each color group reflected that the completion time of 300 lux was faster than that of 50 lux.

Subjective preference

Each rating scale of the NASA-TLX was calculated on a 100-mm scale (0 = lowest workload, 100 = highest workload), and the values of the TLX were compared using ANOVA test. The results between different items (such as total task load, mental, physical and temporal demand, effort, performance and frustration level) are

Table 4. Mean error scores, completion time and subjective preference under each level of the independent variables

Independent variable	*n*	Error scores	Completion time (s)	Overall subjective preference of task load
Ambient illumination				
300 lux	90	76.3	339.9	57.8
50 lux	90	72.2	359.9	58.3
Illuminant colors				
Red	60	78.0	348.0	58.4
Blue	60	77.9	349.0	58.1
White	60	66.9	352.5	57.6
Background colors				
Black	60	68.1	353.5	58.2
Blue	60	79.5	351.2	60.4
Brown	60	75.1	344.8	60.3

Table 5. ANOVA results of dependent variable

Source	DF	Error scores		Completion time (s)		Overall subjective preference of task load	
		F	*p*	*F*	*p*	*F*	*p*
Subject (Block)	9	31.30	0.000	31.83	0.000	61.72	0.000
Ambient illumination (AI)	1	1.91	0.169	**4.68**	**0.032**	0.25	0.617
Illuminant colors (IC)	2	**6.09**	**0.003**	0.09	0.916	0.24	0.785
Background colors (BC)	2	**4.93**	**0.008**	0.32	0.728	0.06	0.937
AI × IC	2	0.21	0.810	0.16	0.853	0.40	0.671
AI × BC	2	2.33	0.101	0.31	0.731	1.73	0.180
IC × BC	4	0.60	0.661	0.44	0.779	0.56	0.692
AI × IC × BC	4	0.57	0.687	1.27	0.286	0.01	1.000

Significant at α=0.05, DF: degree of freedom, *F*: F value, *p*: *p* value

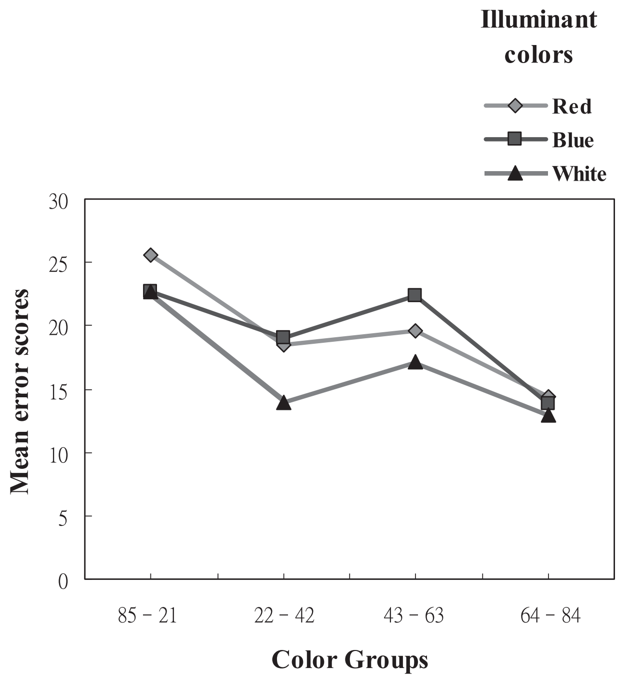

Fig. 4. Comparison of 100-Hue Test performance in the four color groups under different illuminant colors.

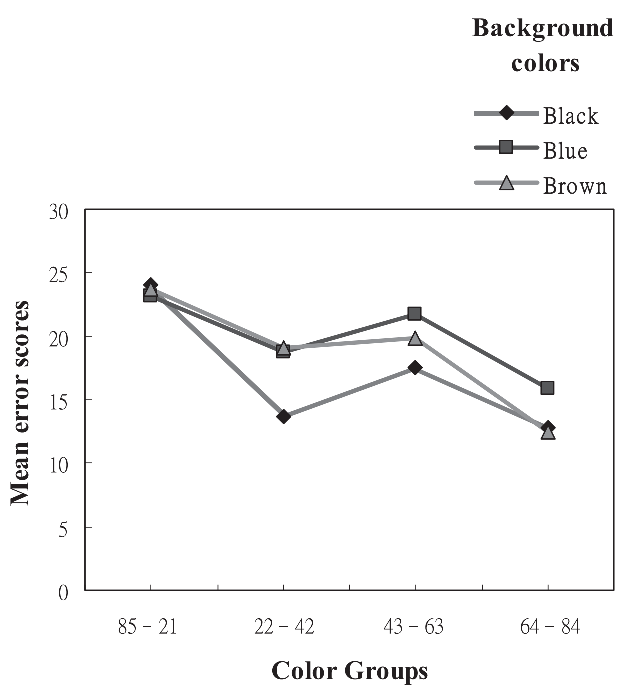

Fig. 5. Comparison of 100-Hue Test performance in the four color groups under different screen background colors.

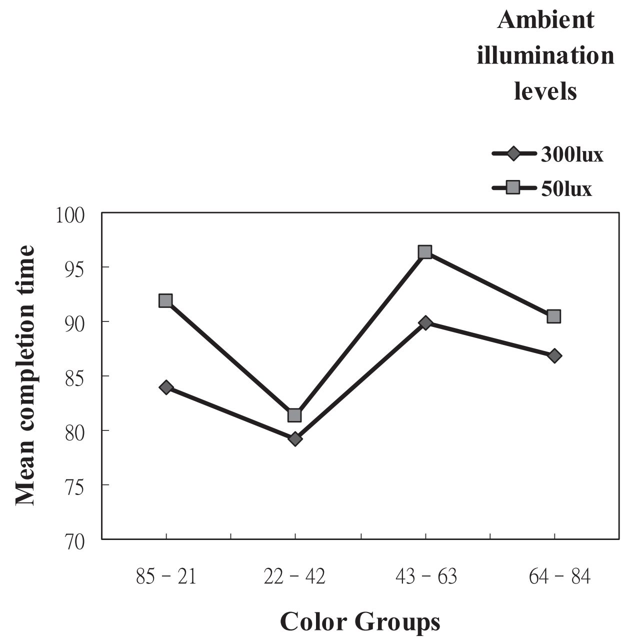

Fig. 6. Comparison of 100-Hue Test performance in the four color groups under different ambient illumination levels.

summarized in Tables 5 and 6. Neither the three-way interaction among illuminant colors, ambient illumination levels, and background colors nor the two-way interactions between each pair of independent variables had a significant impact on subject preference; only the main effect of illuminant colors had a significant impact on the comparison of mental load, although its impact was not significant on other items.

Discussion

This experimental study was designed to examine the performance of color discrimination on the VDTs. The results were discussed as follows.

Illuminant colors

The findings indicated that the error scores under the red and blue illuminant were significantly higher than the error scores under white illuminant, a finding that was consistent with previous studies[12, 14]. It is possible that the subjects were accustomed to the daylight or fluorescent light as a “usual” illumination so they could arrange the shades of colors on the screen more easily, while it may have been more difficult to discriminate the color-matching test of FM-100 colors under the colored illuminant because the subjects were not accustomed to environmental colored illuminant. The perception of colors could be adjustable when the observers persisted 1–2 wk under the environmental colored illuminant[25]. Thus it took a long duration continuously to induce the change in color perception. However, in this study, the duration of working time can not exceed four hours at one time. Therefore, the possibility of human’s perception adjustability has been excluded.

In addition, there was no significant difference in

Table 6. ANOVA results of NASA TLX among different items

Source	DF	Mental		Physical		Temporal		Effort		Performance		Frustration	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Subject (Block)	9	83.53	0.000	116.51	0.000	60.83	0.000	65.61	0.000	15.39	0.000	51.16	0.000
Ambient illumination (AI)	1	0.38	0.539	0.44	0.509	0.03	0.852	0.03	0.868	0.00	0.957	2.00	0.159
illuminant colors (IC)	2	**3.41**	**0.036**	1.09	0.338	0.88	0.418	0.88	0.461	0.60	0.548	0.90	0.408
Background colors (BC)	2	1.56	0.214	2.03	0.135	1.37	0.257	0.01	0.991	2.44	0.091	0.99	0.373
AI × IC	2	0.13	0.882	0.76	0.468	0.26	0.768	1.64	0.197	1.61	0.203	0.49	0.613
AI × BC	2	0.11	0.899	1.57	0.212	0.66	0.519	0.18	0.836	2.25	0.109	1.06	0.350
IC × BC	4	0.33	0.859	0.17	0.935	1.53	0.195	0.81	0.518	0.44	0.781	1.49	0.208
AI × IC × BC	4	0.72	0.581	1.78	0.136	1.17	0.328	0.06	0.994	0.35	0.845	0.29	0.887

Significant at α=0.05, DF: degree of freedom, *F*: F value, *p*: *p* value

how subjects performed in red illuminant and in blue illuminant, but the error scores in group 1 (red to yellow) were significant higher than the error scores in other groups when under the red illuminant (F (3, 236)=12.02, p<0.001). Moreover, the error scores were also significant higher in group 3 (green to blue) under blue illuminant(F (3, 236)=5.83, p=0.001), which could be attributable to the same character of environmental illuminant and target light, for example the blue illuminant confused the human perception of blue hue. Based on the results of this study, the color of the most important target should not be similar to the illuminant color to prevent color confusion by workers.

Besides, the delta E for difference between adjacent colors value did not equal. That may cause illuminant colors dissimilar variations in each group. The results showed that the mean error scores of illuminant colors were significantly different in color group 2 (AverageΔE=4.33, p<0.001) and group 3 (AverageΔE:5.98, p<0.001), but were not significantly either in group 1 (AverageΔE:6.22, p>0.4) or group 4 (AverageΔE:7.66, p>0.6). The delta E value may partially explain why there was differential effect of illuminant color on the error scores for different color groups.

Although the overall subjective preferences shown in the NASA-TLX evaluation were not significant, the effect of mental contribution was statistically significant. The results showed that both the red and the blue ambient lighting had a significantly higher impact on mental factors than did the white lighting. The result was consistent with that of previous studies[14]. Subjects felt a higher mental workload when they were working under either the red or blue lighting condition than they did when working in the white lighting.

Ambient illumination

The factor of ambient illumination had a statistically significant impact on completion time, but not on the error scores or subjective preference. As shown in Fig. 6, the completion time under 300 lux was shorter than 50 lux in each group, a result consistent with that of previous studies[14, 26, 27]. The results further showed that, whether there were illuminant colors or background colors on the screen, subjects seemed to be able to maintain a shorter completion time under the high illumination condition.

Screen background colors

The results of this experiment indicated that background colors of monitor affected the error scores on the color discrimination task. In Fig. 5, the comparison of the errors in four groups of different background colors showed that there were fewer errors for the black background than for the brown background and that the errors in the blue background occurred the most often. The recommendation of background color on the screen was to adopt target/background color combinations with higher color differences, a finding that was consistent with that of previous studies[28]. The reason for this finding could be that the luminance of the background color affected the color discrimination performance.

Conclusion

Experiments in color discrimination for VDT workers in this research revealed that illuminant colors significantly affected color perception when signals with color coding appeared on the screen. Based on the measurement data, the color of the most important target should not be similar to the illuminant color. The results also indicated that a lower luminance of background color could improve color discrimination but that subjects could maintain a shorter completion time on a color discrimination task under high illumination. Designers of workstations for the control room can use these findings to adopt different combinations of colors, appropriate background colors on the screen, and ambient illumination levels to prevent color confusion.

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