The Color Difference Modification between Direct view and Side view after Color Adaptation on LCD

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ABSTRACT

In this study, the color adaptation phenomenon was considered to adjust the CIE DE_{00} formula, and a direct and side view color difference formula on liquid crystal display (LCD) was established. From the results of psychophysical experiments, the formula for considering color adaptation has a high correlation (R^2 = 0.86).

1 INTRODUCTION

There are many factors that affect the quality of the display image, such as color gamut, contrast, resolution, viewing angle, and so on. The illuminating properties of liquid crystal displays cause side-view light leakage and color washout, resulting in a reduced visual angle of view. This defect can be improved by optimizing the hardware, changing materials, and improving the optical design. Generally, the visual viewing angle of the display is based on the color difference between the different viewing angles and the direct view. Most of the studies used CIE DE_{00} to calculate the color difference which is listed in Equations (1) [1], and used the ΔE_{00} = 3 as the color difference threshold of the viewing angle. However, the CIE DE_{00} formula is mainly used to calculate the color difference of side by side colors, so it is not suitable to calculate the color difference seen by the human eye at different angles view at the different time.

$$\Delta E^*_{00} = [(\frac{\Delta L^*}{k_L \cdot S_L})^2 + (\frac{\Delta C^*}{k_C \cdot S_C})^2 + (\frac{\Delta H^*}{k_H \cdot S_H})^2 + R_T(\frac{\Delta C^*}{k_C \cdot S_C} \times \frac{\Delta H^*}{k_H \cdot S_H})]^{1/2} \quad (1)$$

In other literatures, scholars had found that by adjusting the k_L, k_C, and k_H in formula (1) are more consistent with the color differences observed by the human eyes under different viewing condition [2][3], and these three parameters are the factors of lightness difference (ΔL^*), the chroma difference (ΔC^*), and the hue difference (ΔH^*), respectively. The relevant technical documents in CIE mention that the parameter factors can be adjusted according to the occasion, environment, color samples and other factors used by the CIE DE_{00} formula. In general, k_L, k_C, and k_H are set to 1. In addition, lightness (L^*), chroma (C^*), and hue (h^*) are converted from CIE $L^*a^*b^*$ [4]. Most of the studies in the calculation of $L^*a^*b^*$ is based on the full-screen white (L255) as the reference white (X_n, Y_n, Z_n), but the white of the side view is not the same as the front view, and the two viewing angles cannot be observed at the same time, so the $L^*a^*b^*$ which uses the white of the front view seems to be unable to correctly describe the color of side view observed by the human eye. The reference white setting is also a cause of the color difference formula of direct view and side view. The $L^*a^*b^*$ calculation formula is listed in Equations (2) ~ (4).

$$L^* = 116(\frac{Y}{Y_n})^{1/3} - 16 \quad (2)$$

$$a^* = 500[(\frac{X}{X_n})^{1/3} - (\frac{Y}{Y_n})^{1/3}] \quad (3)$$

$$b^* = 500[(\frac{Y}{Y_n})^{1/3} - (\frac{Z}{Z_n})^{1/3}] \quad (4)$$

2 METHOD

In this study, a total of 18 (14 male, 4 female) subjects with normal color vision were asked to observe images in direct (θ = 0°, φ = 0°) and side view (θ = 45°, φ = 0°), and scores were used to evaluate the color difference between the two viewing angles to quantify the feeling. The ΔL^*, ΔC^*, and ΔH^* between the front view and the side view are calculated by substituting different reference white settings into the formula (2) ~ (4), and linear regression was performed with the evaluation score to obtain parameter factors that accorded with the human vision. Then use the most relevant settings to create a color difference model which can effectively evaluate the color difference between direct view and side view.

2.1 Experimental Setup

The psychophysical experiment was performed on vertical alignment (VA) LCD in 65" size with 4K2K resolution. The color characteristic of the LCD measured by the display color analyzer (Konica Minolta CA-310) was listed in Table 1 and the color gamut was plotted in the CIE xy chromaticity diagram as shown in Fig. 1. According to the measurement results, the color coordinates of the white and color gamut were slightly shifted at different viewing angles, but the luminance (Y) varies greatly.

Table 1 Characteristics measurement results of LCD

	Direct view			Side view		
	x	y	Y	x	y	Y
Red (R)	0.6468	0.3344	126.6	0.6500	0.3335	64.6
Green (G)	0.3128	0.6010	521.9	0.3134	0.6083	255.2
Blue (B)	0.1458	0.0641	83.22	0.1449	0.0639	36.29
Black (K)	0.2393	0.2048	0.40	0.2477	0.2533	2.10
White (W)	0.2774	0.2786	733.5	0.2877	0.3016	358.0

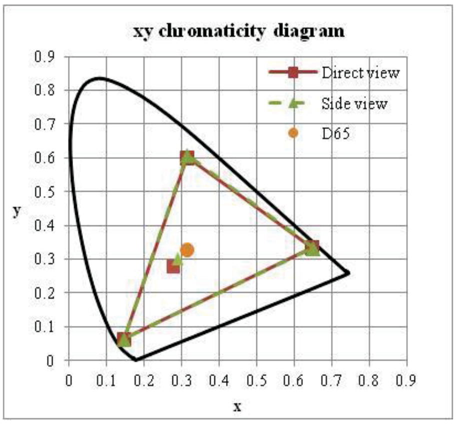

Fig. 1 The color gamuts of direct view and side view

The ambient lighting condition of the experiment was general office lighting (300 lx). The viewing distance was 1.6 times the display height (0.8 m) and the test pattern was a square with a length of 1/18 of the display height. The color area to be evaluated in the test pattern was 1/25 of the total area, and the rest was the background color. All the experimental settings shown in Fig. 2 were referred to the recommendation of literature [5].

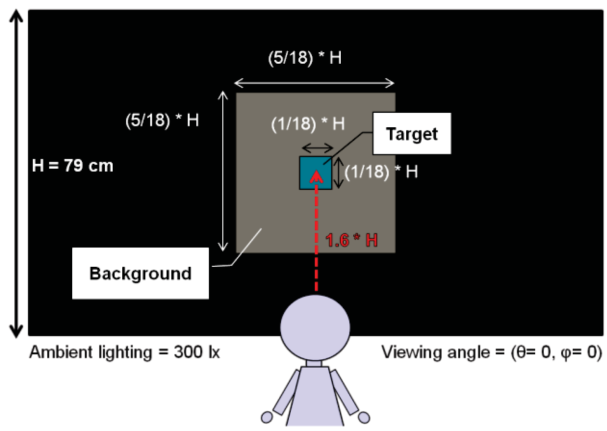

Fig.2 The evaluation conditions of experiment

The 25 colors used in the experiment are listed in Table 2. In addition to the Macbath 24 colors (No.1 ~ No.24), No.25 was neutral gray which was the color of the background, and its luminance was 18% of white.

Table 2 Specifications for target and background colors

No.		R	G	B	No.		R	G	B
1.		8	133	161	14.		133	128	177
2.		187	86	149	15.		87	108	67
3.		231	199	31	16.		98	122	157
4.		175	54	60	17.		194	150	130
5.		70	148	73	18.		115	82	68
6.		56	61	150	19.		52	52	52
7.		224	163	46	20.		85	85	85
8.		157	188	64	21.		122	122	121
9.		94	60	108	22.		160	160	160
10.		193	90	99	23.		200	200	200
11.		80	91	166	24.		243	243	242
12.		214	126	44	25.		118	118	118
13.		103	189	170					

In order to avoid variations in the movement time, viewing angle, viewing distance, etc. between the subjects when the angle of view was switched, the color of the side view was reproduced in the front view. The switch between the front view and the side view was an animation instead of moving the position to switch the view. Through a simple evaluation experiment, the subjects indicated that the process of the viewing angle change was set to 3.5 seconds, which was the most realistic.

From the results of the measurement (Fig. 3), it could be found that reproduced color was very close to the real color in the side view, and all the color differences are smaller than ΔE_{00}=1.2.

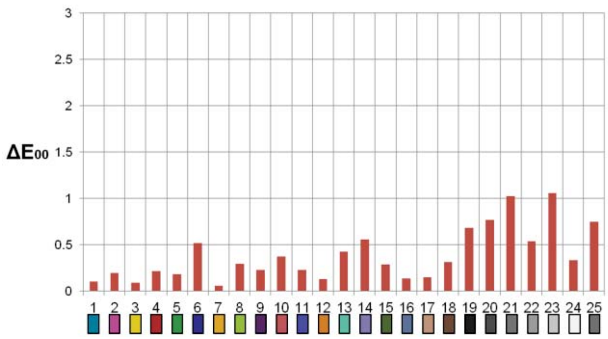

Fig. 3 The color difference between the actual and the simulated of side view

2.2 Experimental design

The evaluation experiment was divided into two parts, the first part will ask the subjects to evaluate the color difference between the direct and side view by using the 5-point Likert, and the second part was to sort the ΔL*, ΔC*, ΔH*. The five color difference levels listed in the Table 3 which were hardly (1 point, 0.0 ≦ ΔE_{00} < 1.5), noticeable (2 points, 1.5 ≦ ΔE_{00} < 3), appreciable (3 points, 3 ≦ ΔE_{00} < 6.0), obvious (4 points, 6.0 ≦ ΔE_{00} < 12.0), and very obvious (5 points, 12.0 ≦ ΔE_{00}). The perceived level of color difference was based on standard technical document [6].

Table 3 Perception of color difference [6]

Level	ΔE_{min}	ΔE_{max}	Perception of color difference
1	0.0	1.5	Hardly
2	1.5	3.0	Noticeable
3	3.0	6.0	Appreciable
4	6.0	12.0	Obvious
5	12.0	∞	Very Obvious

Before the main experiment, the subjects will practice converting the feeling of color difference into scores by using a 5-point Likert scale through the pre-experiment, and the concept of ΔL*, ΔC*, ΔH* will be explained. In the pre-experimental, red, green, and blue were used as exercises. Fig. 4 showed red as an example, the right part of the figure was the ΔL*, ΔC*, ΔH* from top to bottom. Each small color block was divided into two colors, the right side was the primary color, and the left side was the color block that adjusted the L*, C* or H* accorded to the lower limit of the color difference. The left part of the figure could simulate direct and side view switching, and the subject could operate and repeat the view to convert the perception of color difference into evaluation score. The left part of the figure could simulate the conversion of the view, and the evaluators could repeatedly switch by themselves.

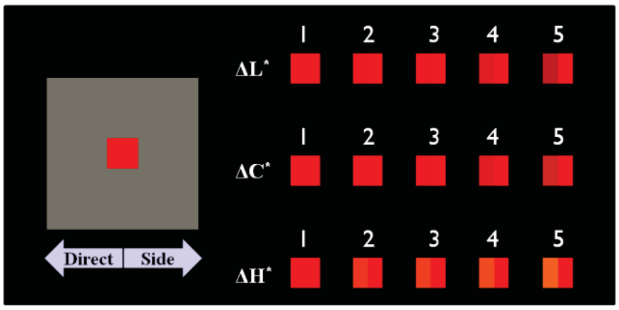

Fig. 4 Pre-experimental design

3 RESULTS

The color differences between the direct view and side view were calculated by the DE_{00} formula and converted to 1-5 levels through the Table 3. From the comparison between the human factor evaluation score and the calculation result of the DE_{00} formula in Fig. 5, it could be found that it was not exactly the same. Therefore, the DE_{00} color difference formula need to be adjusted to match the view change of human vision on display.

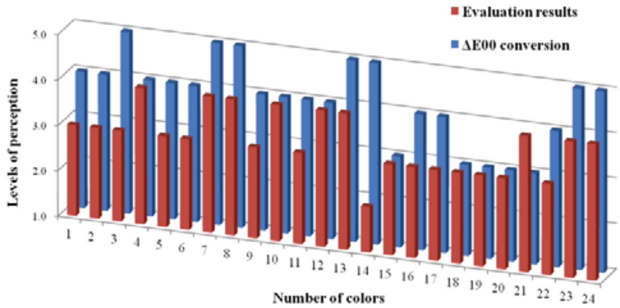

Fig. 5 DE_{00} formula calculation and evaluation score comparison

Therefore, the evaluation score was taken as the target, k_L, k_C, and k_H (Equations 1) were obtained through linear regression, and the color difference formula between the direct view and the side view conformed to the evaluation result was established. In addition, the reference white settings for calculating L*a*b* (Equations 2 to Equations 4) in three different cases were listed in Table 4, thereby finding the setting that best matched the color change under the viewing angle switching.

Table 4 Perception of color difference

Settings	Reference white	
	The color of direct view	The color of side view
Without Color adaptation	$X_n=X_{direct\,L255}$ $Y_n=Y_{direct\,L255}$ $Z_n=Z_{direct\,L255}$	$X_n=X_{direct\,L255}$ $Y_n=Y_{direct\,L255}$ $Z_n=Z_{direct\,L255}$
Color adaptation	$X_n=X_{direct\,L255}$ $Y_n=Y_{direct\,L255}$ $Z_n=Z_{direct\,L255}$	$X_n=X_{side\,L255}$ $Y_n=Y_{side\,L255}$ $Z_n=Z_{side\,L255}$
Lightness adaptation	$X_n=X_{direct\,L255}$ $Y_n=Y_{direct\,L255}$ $Z_n=Z_{direct\,L255}$	$X_n=X_{direct\,L255}\times(Y_{side\,L255}/Y_{direct\,L255})$ $Y_n=Y_{direct\,L255}\times(Y_{side\,L255}/Y_{direct\,L255})$ $Z_n=Z_{direct\,L255}\times(Y_{side\,L255}/Y_{direct\,L255})$

The first setting was without color adaptation, the color space was based on direct view as the standard, and the reference whites of both were white of the direct view; the second setting considered the color adaptation phenomenon. The direct view and the side view were treated as independent color spaces, and used the respective white as the reference white; the third type was similar to the second type, but only considered the lightness adaptation. The direct white was normalized to the lightness of the side view white as a reference white for the side view, and the direct view used its own white as the reference white.

The linear regression results were listed in Table 5. The correlation coefficient between the CIE DE_{00} formula and the evaluation results was the lowest (R^2 = 0.24). Among the three reference white settings, the highest correlation with the evaluation results (R^2 = 0.86) was the regression formula of the color adaptation setting, which was most in line with the perception of color difference between the direct view and the side view switched on the LCD. The second was without color adaptation, and the third was lightness adaptation. The weights of the three regression formulas were $1/k_C > 1/k_H > 1/k_L$, and in the color adaptation, the weight of the ΔC* was greatly improved.

Table 5 Parametric factors of formulas

	$1/k_L$	$1/k_C$	$1/k_H$	R^2	P-value
DE_{00} formula	1	1	1	0.24	-
Without color adaptation	0.25	0.35	0.27	0.70	$p < 0.05$
Color adaptation	0.20	0.76	0.29	0.86	$p < 0.05$
Lightness adaptation	0.26	0.30	0.27	0.57	$p < 0.05$

From the psychophysical results, the reference white setting of the color adaptation was most consistent with the questionnaire results. The reason was that when viewing display, the white at different viewing angles was not the same, and the difference between the two colors was not evaluated side by side, so the human will produce a color adaptation phenomenon, which causes DE_{00} to be inconsistent with the questionnaire result.

In the questionnaire evaluation results of 24 colors (Table 6), the main component of the color difference between the direct view and the side view was 9 colors of ΔL*, 14 colors of ΔC*, and only 1 color of ΔH*. This showed that the lightness and chroma were the main changes in the color when the viewing angle was different on the LCD. The optical calculation results of the DE_{00} formula, adaptive regression formula and uncolored adaptive regression formula were consistent with the evaluation results, while the main component of the lightness adaptive regression formula was lightness, which was quite different from the questionnaire result.

Table 6 Main components of color difference in different formula

Color difference analysis \ Main component	ΔL*	ΔC*	ΔH*
Questionnaire evaluation result	**9 colors**	**14 colors**	**1 color**
ΔE_{00} formula	**12 colors**	**11 colors**	**1 color**
Without color adaptation formula	**10 colors**	**13 colors**	**1 color**
Color adaptation formula	**12 colors**	**12 colors**	**0 color**
Lightness adaptation formula	**21 colors**	**3 colors**	**0 color**

4 CONCLUSION

In order to correctly describe the human vision for color difference between direct view (θ = 0°, φ = 0°) and side view (θ = 45°, φ = 0°) on LCD, psychophysical experiment was conducted in this study. From the experimental results, the reference white setting of the color adaptation was most consistent with the human vision, and the biggest weight of regression was ΔC*, the ΔL* was second, the smallest was ΔH*. The color optics was substituted into the color adaptive regression formula, and the principal components of the color difference are also consistent with the human factor evaluation. Therefore, through this study, a formula of color difference between direct view and side view conforming to human vision on LCD was established. In the future, formulas will be introduced into the algorithm to reduce the impact of color washout on LCD.

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