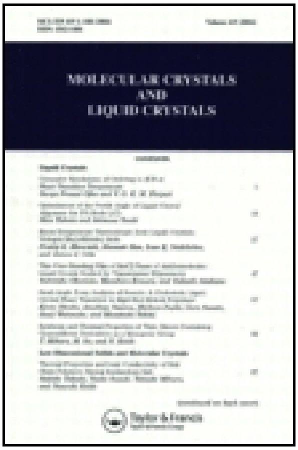

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Criteria of Color Contrast in a Nematic Liquid Crystal Display

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Color contrast in a nematic liquid crystal display is defined experimentally. Liquid crystal cell shows a positive dielectric anisotropy and is operated in a tunable birefringence mode. Munsell color chips are used as background color. Colorimetric data are shown in the 1976 CIE(L^*, a^*, b^*) color scale. First, a predict equation of color shift induced by background color is derived and shows a good agreement with the result of experiment. Second, criteria of color contrast is established by taking into account the color shift. The values of criteria nearly coincide with that of psychophysical experiment by single-stimulus method, and the validity of criteria is confirmed.

I INTRODUCTION

Many investigations of color display devices have been reported.[1–7] Among them, nematic liquid crystal devices (LCDs) are utilized in practice. They are grouped into three modes; TB (tunable birefringence) mode,[1–3] GH (guest host) mode,[4,5] TN (twisted nematic) mode[6,7] with dichroic polarizers. The color of the TB mode is the same as the interference color of thin film essentially. The color of the other mode is due to the dichroism of dye.

The main purpose of the present paper is to establish the criteria of color contrast in a transmission type. We deal with the TB mode as an example.

When the color display devices are designed, knowledge of a predict equation of color shift induced by background color is required for any quantitative theory of color contrast. For various test samples, there are many reports[8] of color appearance utilizing the technique of binocular color matching.[9] However, there is very little quantitative data using a liquid crystal device as a test sample. Liquid crystal (LC) used in this experiment is a mixture of MBBA 80 wt% and BBCA (butoxybenzylidenecyanoaniline)

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20 wt%. LC molecules are aligned almost parallel to the electrode at the quiescent condition by oblique evaporation[10] of SiO. Temperature is controlled to 25°C by a thermoelement device. Cell thickness is 24.2 μm.

II DERIVATION OF COLOR SHIFT

Derivation of color shift induced by background color is done as follows. From the aspect of estimating color shift, it is convenient to generate an arbitrary color in LCD. A familiar method of obtaining an arbitrary color is to use an Ulbrich sphere.

Figure 1 shows an optical system of apparatus. The principle of this apparatus is the same as that of the binocular colorimeter.[9] Color temperature of a point light source S_1 or S_2 is 6500 Kelvin and is realized by the combined use of the standard lamp for colorimetry and a correction filter. A xenon arc lamp S_3 is used for vertical illumination of about 180 lux. Transmitted light through the LC cell or color filter enters the Ulbrich sphere U_1 or U_2 and shown in the widow W_1 or W_2 as an arbitrary color.

Figure 2 shows the backgrounds. Munsell color chips are used as two backgrounds. Two 20- by 13-cm backgrounds are placed side by side along their 20-cm side and have 1.3-cm diameter circular window at their centers. The right-hand background and window are referred to as standard background and matching the sample color; and those at left are referred to as second background and test sample color. Munsell color chips 5R–, 5G–, 5B–5/6 are used as second background and N–5 is used as standard background. Visual field in measurement is 4°. The task of five observers is to adjust the color filter F_2 in Figure 1 so that the test sample color and matching sample color look equally.

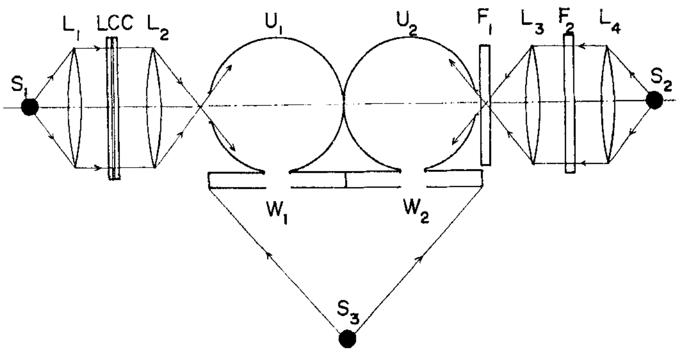

FIGURE 1 Optical system of apparatus. LCC: liquid crystal cell. L_i (i = 1, 2, 3, 4): lens. F_i(i = 1, 2): S_i(i = 1, 2, 3): point light source. U_i(i = 1, 2): Ulbrich sphere W_i(i = 1, 2): window.

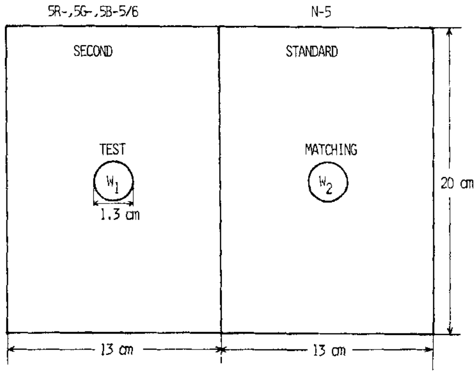

FIGURE 2 Two backgrounds and windows.

The LC cell has a square pattern consisting of 25 picture elements. The color of each element is controlled electrically by varying the applied voltage. On the other hand, the area in the square window of each color filter is controlled mechanically by shifting these color filters. In order to obtain the point of subjective equality,[11] the method of adjustment[11] is employed using the psychophysical method. The order of shifting color filters is given as follows; first, shift from the horizontal- to the vertical-direction and next reverse the order. This procedure is repeated in turn ten times. The speed of shifting is 0.2 cm/sec. The limited time for one procedure is defined within 60 seconds.

In order to establish the predict equation of color shift, some preliminary observations are made as follows. First, saturation and lightness of a test sample color are kept constant and hue is only changed for three backgrounds. Second, lightness or saturation is changed for the dominant wavelength, showing the maximum color difference, from the chromaticity coordinates of the background to that of the test sample color.

Colorimetric data are shown in the 1976 CIE (L^*, a^*, b^*) color scale. The quantities of L^*, a^*, b^* are defined as follows:

$$L^* = 116(Y/Y_0)^{1/2} - 16 \tag{1}$$

$$a^* = 500[(X/X_0)^{1/3} - (Y/Y_0)^{1/3}], \tag{2}$$

$$b^* = 200[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}], \tag{3}$$

$$X/X_0,\ Y/Y_0,\ Z/Z_0 > 0.01, \tag{4}$$

where X_0, Y_0, Z_0 are the tristimulus values of specified achromatic lights using in illumination. X, Y, Z are the tristimulus values of object color and value of Y_0 is normallized in such a way that $Y_0 = 100$.

From the results of observations, a predict equation based on the induction theory[12] is assumed as follows:

$$\Delta a^* = K_1 \cdot \Delta a_b^* + K_2, \tag{5}$$

$$\Delta b^* = K_3 \cdot \Delta_b^* + K_4, \tag{6}$$

where $\Delta a^*(\Delta b^*)$ is the difference between the chromaticity coordinates of a matching sample $a_m^*(b_m^*)$ and that of a test sample $a_t^*(b_t^*)$, or $\Delta a^* = a_m^* - a_t^*$ $(\Delta b^* = b_m^* - b_t^*)$; $\Delta a_b^*(\Delta b_b^*)$ is the difference between the chromaticity coordinates of the background in the matching sample side $a_{bm}^*(b_{bm}^*)$ and that of the background in the test sample side $a_{bt}^*(b_{bt}^*)$, or $\Delta a_b^* = a_{bm}^* - a_{bt}^*(\Delta b_b^* = b_{bm}^* - b_{bt}^*)$; K_i $(i = 1, 2, 3, 4)$ are the coefficients.

Substituting the colorimetric data in Eqs. (5), (6), we estimate the coefficients K_i for each observation by using a least square method. Figure 3 shows an example of the predict equation and plots of measured data for each background. Symbol R stands for the correlation coefficient. From the result of Figure 3, high correlation coefficients are obtained and the validity of the predict equation is confirmed.

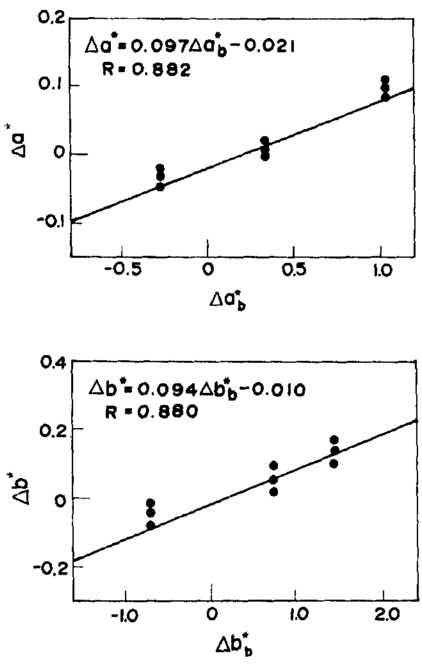

FIGURE 3 An example of a predict equation and plots of measured data for each background.

III CRITERIA OF COLOR CONTRAST

The equation of criteria of color contrast is defined as follows:

$$\text{Color Contrast} = (\Delta E^*_{ab}) - M_1 \cdot M_2(\Delta E^*_{ab})_{cs}, \tag{7}$$

where ΔE^*_{ab} stands for the color difference. This is formulated as the next equation.

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}, \tag{8}$$

where ΔL^* is the difference of coordinates of two points in a similar manner as Δa^*, Δb^*, and subscript cs stands for the color shift.

The first term is the color difference between the test sample color and background color. The second term is the color difference arising from the color shift induced by background color. Symbol M_1 is the correction constant correlating to the dominant wavelength. Symbol M_2 is the correction constant correlating to the saturation. These values are decided from the results of the colorimetric data and shown in Table I.

TABLE I

Correction constants

M_1	3.5	$400 < \lambda_d \leqslant 500$ nm
	4.0	$500 < \lambda_d \leqslant 600$ nm
	2.5	$600 < \lambda_d \leqslant 700$ nm
M_2	5.0	Sat $\leqslant 50\%$
	7.0	Sat $> 50\%$

In Table I, symbol λ_d stands for the dominant wavelength. The dominant wavelength value of the maximum color difference for each background exists in three ranges. The value of color difference as a function of saturation at the dominant wavelength mentioned above increases according as the increasing of saturation of the background color. On the other hand, the value of color difference as a function of lightness only shows a slight variation.

In order to confirm the criteria, psychophysical experiment is executed for five observers. The single-stimulus method[11] is employed as the psychophysical method. That is, two stimuli of the combination of test sample color and background color are shown for each observer at random. Table II shows the results of calculation of Eq. (7) and psychophysical experiment for various background colors.

TABLE II

Results of calculation and psychophysical experiment.

Test Sample Color λ_d(nm)	L^*	Sat(%)	Background Color	(ΔE^*_{ab})	$(\Delta E^*_{ab})_{cs}$	Criteria in eq. (7)	Experiment
450	77	30	5YR-7/6	18.62	0.33	12.81	10.2
490	53	20	5RP-4/6	16.35	0.24	12.33	9.4
510	67	50	5Y-6/8	12.89	0.25	7.89	6.5
610	83	70	5P-5/6	9.42	0.24	5.39	3.1
630	77	80	5BG-5/6	17.58	0.26	13.03	11.4

In this Table, symbol (ΔE^*_{ab}), $(\Delta E^*_{ab})_{cs}$ correspond to the first and second terms in Eq. (7). The values of criteria nearly coincide with the values of the psychophysical experiment. From these results, the validity of criteria of color contrast is confirmed.

IV CONCLUSION

The criteria of color contrast is studied. First, color shift induced by background color is estimated. The predict equation of color shift is in good agreement with the experimental data of each of five observers. Second, the criteria of color contrast is established. The values of the criteria nearly coincide with that of psychophysical experiment. From these results, we can confirm the validity of the criteria.

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