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Colorimetric and Ergonomic Evaluation and Optimization of LCDs

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Colorimetric and Ergonomic Evaluation and Optimization of LCDs

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A review of colorimetric and ergonomic evaluation of nematic liquid crystal displays is given. The characteristics of the following terms are examined colorimetrically and their optimization is described: (1) two kinds of practical polarizers developed for twisted nematic liquid crystal displays; (2) multiplexability of twisted nematic liquid crystal displays with these polarizers; (3) guest-host liquid crystal display without a polarizer (and a double-layered one); (4) the color gamut of tunable birefringence and guest-host liquid crystal displays with a polarizer.

INTRODUCTION

Liquid crystal displays (LCDs) permeate everyday life, such as watches, calculators, personal computers, games, etc. The diffusion of LCDs requires us to establish good legibility and an appropriate expression for their perceptual properties.

The development of LCDs, aiming at realizing good legibility, seems to indicate the following two directions: one is to realize a good black and white LCD, and the other is a good color LCD. The twisted nematic (TN) mode with neutral polarizers is used widely for the black and white display, but there is still a need to improve its legibility.

The following four modes are known as color LCDs: (1) the tunable birefringence (TB) mode; (2) the guest-host (GH) mode with pleochroic or black dyes; (3) the TN mode with selective color polarizers; and (4) the black shutter mode, i.e. a painted pattern is shown as an information display by opening or closing the black shutter of a TN or a black GH liquid crystal medium situated in front of the painted panel. Some of these modes are used in a reflective type; it has the advantage of nonemissive display and a special feature is its low power consumption of LCDs. In contrast to the reflective type, all kinds of transmissive types show a beautiful color when they are illuminated by an appropriate light source from behind the cell.

An appreciable advance in LCD technology has encouraged us to develop new practical color LCDs with novel applications;[1] an example is a TN LCD panel for automobile dashboards with printed patterns on selective polarizers as shown in Figure 1. The quality of color LCDs which have been developed so far is still inferior to that of color CRT. However, many efforts to improve this quality have been going on for a long time. It is important for us to acquire the practical-use application of the merits of LCDs.

From the above background and reasons, we have done an evaluation and optimization of TN and GH mode LCDs from the standpoint of the colorimetric and ergonomic methods. These methods are ranked higher than the physical or psychophysical methods.

The purpose of this paper is to describe the optimization of both static and dynamic performances, to review the colorimetric and ergonomic evaluation, and further to examine the color gamut in TB and GH mode LCDs.

We used the 1976 $L^*U^*V^*$ or 1931 XYZ chromaticity diagram in case of need. The $L^*U^*V^*$ chromaticity diagram can be easily obtained from the linear conversion of the XYZ diagram.

COLORIMETRIC EVALUATION

The trichromatic specifications of the $L^*U^*V^*$ color scale, i.e. $(L^*u^*v^*)$ color scale, are defined as follows:[2]

$$L^* = 116(Y/Y_0)^{1/3} - 16, \qquad Y/Y_0 > 0.01 \tag{1}$$

$$u^* = 13L^*(u' - u_0'), \tag{2}$$

$$v^* = 13L^*(v' - v_0'), \tag{3}$$

where Y_0 is the luminance factor of the perfect reflecting diffuser and u_0' and v_0' stand for the (u', v') chromaticity coordinate for the white point at a given

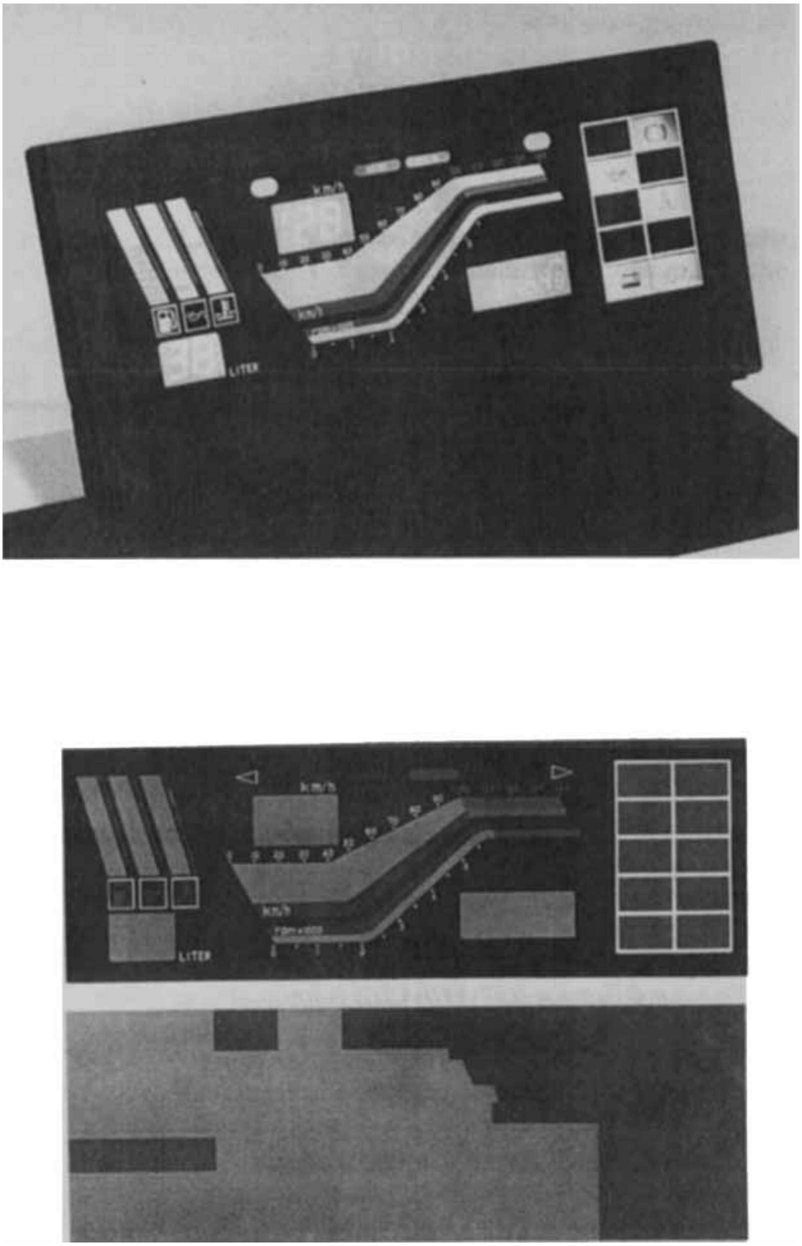

FIGURE 1 Color photography of automobile dashboard (Sanritsu Electric Co. Ltd.).

color temperature. The chromaticity coordinates (u', v') are expressed by the following equations:

$$u' = \frac{4X}{X + 15Y + 3Z}, \tag{4}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}, \tag{5}$$

where X, Y, Z are the tristimulus values in the CIE 1931 standard colorimetric system. The tristimulus values X, Y, Z are formulated as follows:[3]

$$X = \frac{\int_{\text{vis}} \bar{x}_\lambda P_\lambda T_\lambda \, d\lambda}{\int_{\text{vis}} \bar{y}_\lambda P_\lambda \, d\lambda}, \tag{6}$$

$$Y = \frac{\int_{\text{vis}} \bar{y}_\lambda P_\lambda T_\lambda \, d\lambda}{\int_{\text{vis}} \bar{y}_\lambda P_\lambda \, d\lambda}, \tag{7}$$

$$Z = \frac{\int_{\text{vis}} \bar{z}_\lambda P_\lambda T_\lambda \, d\lambda}{\int_{\text{vis}} \bar{y}_\lambda P_\lambda \, d\lambda}, \tag{8}$$

where P_λ and T_λ are the spectral power distribution of the illuminant at a given temperature and the spectral transmittance of a sample device. The quantities $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ are the color matching functions of the CIE 1931 standard colorimetric observer. These three integrations were done in a visible region from 380 to 700 nm.

The color difference ΔE^*(1976 CIE) is formulated as follows:[2]

$$\Delta E^* = [\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}, \tag{9}$$

where ΔL^*, Δu^*, Δv^* are the differences between two points represented in the $L^*U^*V^*$ chromaticity diagram. These two points in the color space correspond to the ON and OFF states for LCDs.

The fundamental characteristics of the polarizers and dye stuffs, and the operating performance of LCDs are expressed by the following terms: (1) whiteness; W$^{\circledR}$, (2) blackness; B$^{\circledR}$, (3) color difference ratio; CDR for monocolor display. We defined these terms as shown in Figure 2:

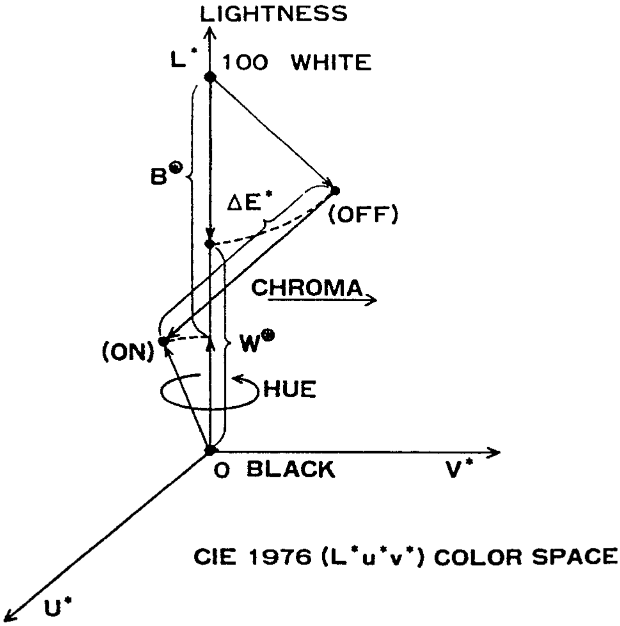

FIGURE 2 CIE 1976 L*U*V* color space.

$$W^{\circledR} = 100 - [(100 - L^*)^2 + (u^*)^2 + (v^*)^2]^{1/2}, \tag{10}$$

$$B^{\circledR} = 100 - [(L^*)^2 + (u^*)^2 + (v^*)^2]^{1/2}, \tag{11}$$

$$CDR = \Delta E^*(\text{ON-OFF})/[100 - W^{\circledR}]. \tag{12}$$

NEUTRAL POLARIZERS[4]

We investigated the colorimetric characteristics of two kinds of practical polarizers developed especially for TN mode LCDs; one is a neutral gray type (L-82-18) and the other is a bluish-gray type (SH-12-18). Spectral transmittance of the neutral polarizers were measured by a doublebeam spectrophotometer. The results are shown in Figure 3. The integration with respect to λ is computed by the gaussian quadrature method. The obtained colorimetric data of the polarizers together with the color contrast ratio are given in Table I. In this Table, the transmittance and contrast ratio is obtained for white light.

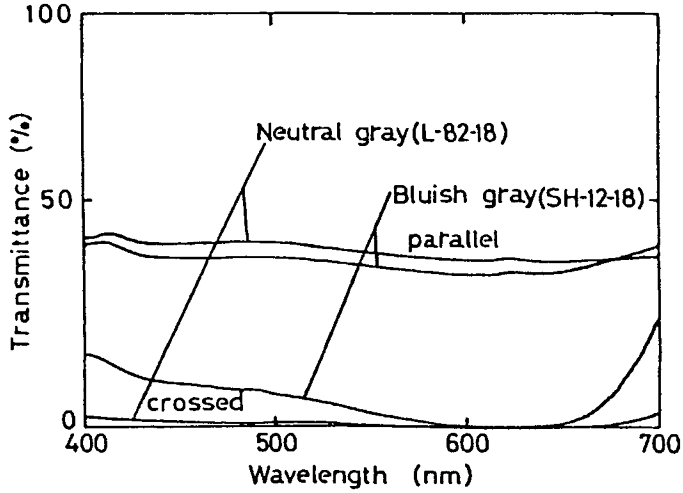

FIGURE 3 Spectral transmittance of the neutral gray and the bluish-gray polarizers for parallel and crossed states.

We examined the relation between the transmittance T and the lightness L^* by rotating the polarizer mechanically from a parallel state to a crossed state and observed the color difference ΔE^*, between the two states. Figures 4, 5, and 6 show the results. In order to determine the shape of the curves in Figure 4, we applied two kinds of functions to a least squares method: one is a logarithmic function; the other is a cube root function with respect to the transmittance T. It was concluded that the transmittance is a logarithmic function with respect to the perception of human eyes for both polarizers. Since the influences of the hue and the chroma are very small at the crossed state for the neutral gray polarizer, the characteristic of the color difference ΔE^* vs the contrast ratio C follows a

TABLE I

Experimental values of neutral polarizers

Polarizers	States	L^*	u^*	v^*	$T(\%)$	ΔE^*	C
Neutral gray	parallel	68.7	6.93	−1.86	41.7	57.4	19.2
(L-82-18)	crossed	12.2	−3.22	1.28	2.17	0	1
Bluish-gray	parallel	62.9	−2.49	−7.79	40.0	46.1	3.70
(SH-12-18)	crossed	31.9	−23.7	−34.6	10.8	0	1

T—Transmittance with white light; C —Contrast ratio with white light.

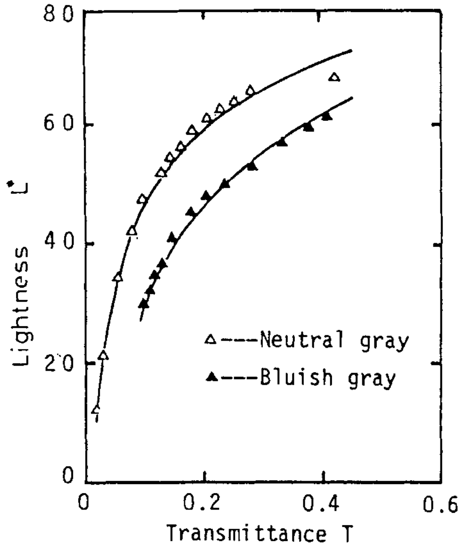

FIGURE 4 Lightness vs transmittance characteristic of the neutral gray and the bluish-gray polarizers.

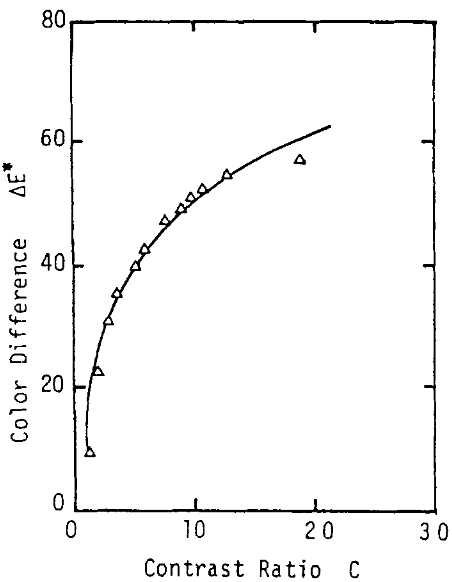

FIGURE 5 Color difference vs contrast ratio characteristic of the neutral gray polarizer.

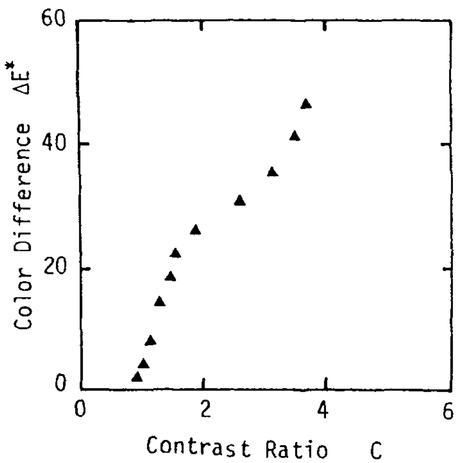

FIGURE 6 Color difference vs contrast ratio characteristic of the bluish-gray polarizer.

logarithmic relation as shown in Figure 4. The color vectors in the $L^*U^*V^*$ color space coincide roughly with the L^* axis for the neutral gray polarizer. On the other hand, the characteristics of the bluish-gray polarizer become complicated because the influences of the hue and chroma become more significant than in the case of the neutral gray polarizer.

The neutral gray polarizer is superior to the bluish-gray polarizer; the maximum values of ΔE^* and C are about 57 and 20 for the neutral gray polarizer, and 46 and 4 for the bluish-gray polarizer. These values mean that the change in the color difference becomes smaller compared with the contrast ratio; the contrast ratio becomes larger as the transmittance at the crossed state becomes smaller. The conventional estimation for an achromatic display using the transmittance T or contrast ratio C cannot correspond to the perception of human eyes. Thus, we must treat the neutral polarizers colorimetrically as well as the dichroic ones, especially the bluish-gray polarizers. This means that the electro-optical capabilities, such as multiplexability, should be treated in terms of the quantities obtained colorimetrically.

DYNAMIC PERFORMANCE OF TN LCDS[5]

Achieving high multiplexability of the LCD is now one of the most important tasks. Multiplexability is the maximum number of row lines, for example, of a multiplexed matrix display, and is known to be directly dependent on the optical response vs the voltage curve of the device, especially on its threshold sharpness. We have investigated the dynamic colorimetric characteristics of LCDs such as multiplexability.

Table II shows the experimental conditions, including the samples, polarizers and measurements. LCDs were operated in a TB mode, the liquid crystals used were a cyanobiphenyl mixture E-18(E. Merck) and the biasing method was of the RMS selection scheme proposed by Alt and Pleshko.[6] For comparison, conventional contrast ratio measurements were also performed using a photomultiplier as a detector and a $W\text{-}I_2$ lamp(4300 K) as a light source.

We examined the following terms: first, how the colorimetric quantities such as ΔL^* and ΔE^* of TN LCD panels decrease with the increase of the inverse of the duty ratio of the applied pulses, which approximates well to the number of scanned (multiplexed) lines N of a matrix display; second, how these colorimetric behaviors differ from the contrast ratio determined by conventional physical photometry.

Figure 7 and 8 show the results for the TN cell with the neutral gray and bluish-gray polarizers. These results were measured for ON and OFF states of the normally closed-type TN cell in which the polarizers were set parallel to each other. Values of ΔL^* decrease with the lines N, as does the contrast ratio C. But C decreases more rapidly than in the case of ΔL^*. Similar decreasing behaviors of ΔE^* with lines N can be seen in Figures 9 and 10; comparing these with the data shown in Figures 7 and 8, it can be seen that the decreasing rates of ΔE^* are very slow compared with those of ΔL^*. This difference may be understood by considering the contribution of both the hue and the chroma to the color difference ΔE^*, whereas ΔL^* comes only from the subjective brightness to the human eye.

Another important point to be gathered from Figures 7 to 10 is that the multiplexability proper of a TN LCD is strongly dependent on the nature of the polarizers; the neutral gray type is superior to the neutral bluish-gray type for multiplexing.

TABLE II

LC cell and applied voltage

Liquid crystal	E-18
Treatment	rubbing
Thickness	18 μm
Polarizers	L-82-18, SH-12-18
Biasing method	RMS bias
Signal frequency	1 kHz
Threshold voltage	1.4 V

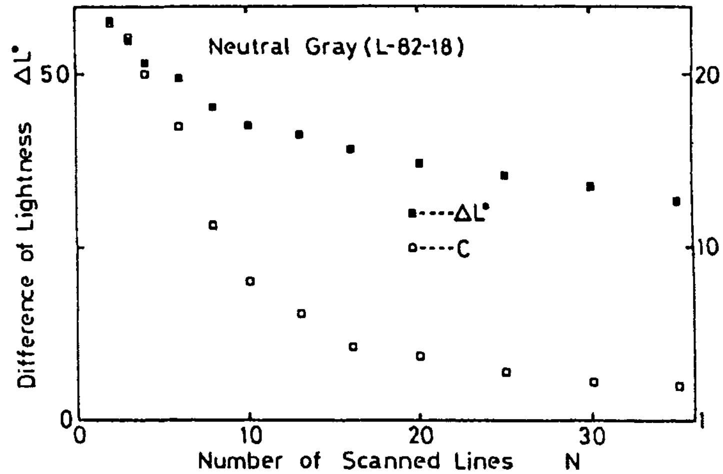

FIGURE 7 Difference of lightness and contrast ratio vs number of scanned lines for neutral gray polarizer.

Let us now discuss the origin of the difference in the rates of decrease with N between the colorimetric data ΔE^* (or ΔL^*) and the conventional contrast ratio C. In a previous article, we showed that ΔE^* (or ΔL^*) of a TN LCD cell with neutral polarizers is expressed by ΔE^* (or ΔL^*) $= a + bT^{1/3}$, where T is the transmittance in % through the cell

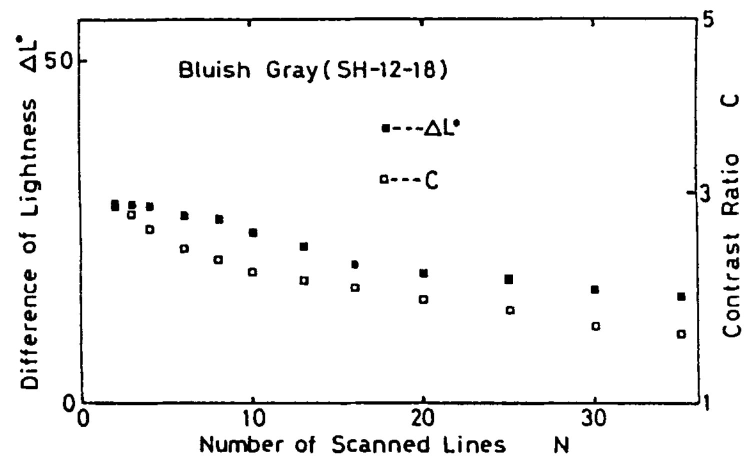

FIGURE 8 Difference of lightness and contrast ratio vs number of scanned lines for bluish-gray polarizer.

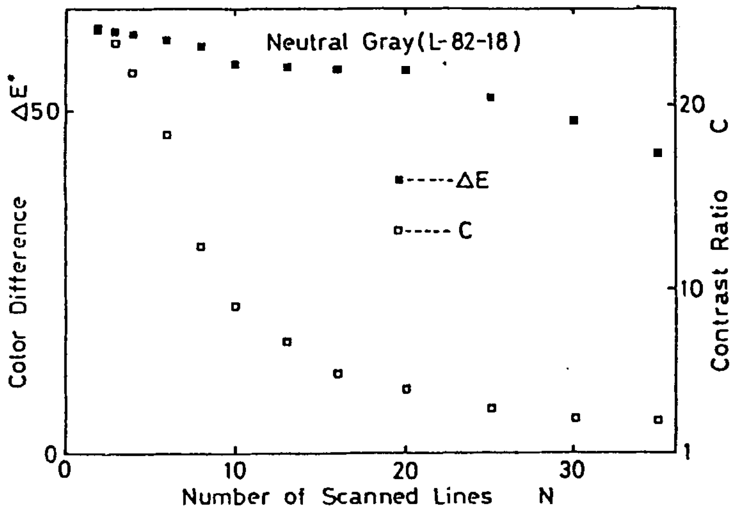

FIGURE 9 Color difference and contrast ratio vs number of scanned lines for neutral gray polarizer.

measured by a photomultiplier and a white light source system, and *a* and *b* are constants; this relationship expresses the strong nonlinearity of the subjective light intensity of the human eye which will be valid for the case

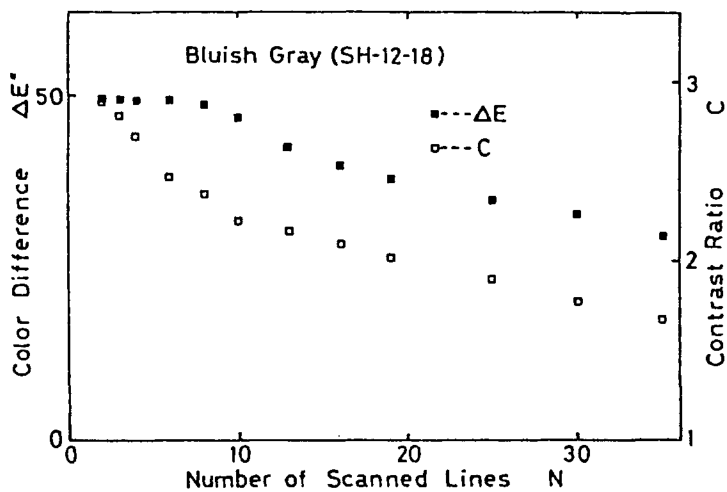

FIGURE 10 Color difference and contrast ratio vs number of scanned lines for bluish-gray polarizer.

where the OFF state of the LCD is dark. This nonlinearity causes a larger steepness in the threshold characteristic in ΔE^* (or ΔL^*) vs applied voltage V, compared with that in C (or T) vs V. Alt and Pleshko[6] showed that the steeper the threshold sharpness, the larger the multiplexability. The difference in the multiplexability evaluated colorimetrically and that obtained by physical photometry can be explained from this consideration. Thus we can say that the multiplexability limit of a TN LCD composed of commercially available materials (LC:E-18, polarizer: L-82-18) will be about 30 lines if it is evaluated colorimetrically, whereas it is known to be about 10 lines for conventional materials if it is determined by physical photometry.

Next we will discuss another shortcoming in the conventional estimation from the data of Figures 9 and 10. The color difference at $N = 2$ (normalizing point) of a neutral gray and a bluish-gray display are almost the same (59 and 50), whereas the contrast ratios are 23 and 2.9. There is a difference of a factor of eight in these figures; however, we cannot actually recognize such a large difference as is indicated by the values of C.

Finally, we examined the chromaticity coordinates of both ON and OFF states of the two kinds of TN cells. Figure 11 shows the results. The chromaticity coordinates of the ON states of both types of LCDs have almost the same color, which are represented by a large dot and a triangle. They are very close to the white point. The chromaticity coordinates of the OFF states of the *TN* cell with the bluish-gray polarizers are almost fixed even if N changes and these are represented by a large circle. However, the

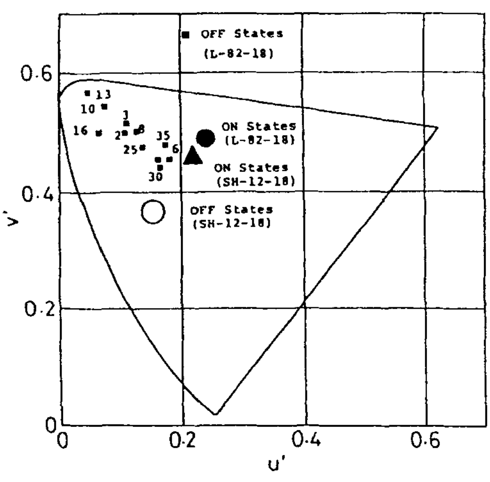

FIGURE 11 CIE 1976 (u',v') chromaticity coordinates of TN mode LCDs with L-82-18 and SH-12-18; numbers appearing beside the squares are the number of scanned lines in the matrix LCD.

points for OFF states of the cell with neutral gray polarizers are scattered in the green color region of the chromaticity diagram when N changes systematically from 2 to 35. These numbers are shown beside the small black squares; this phenomenon is known as color formation in a relatively thin TN cell and can be understood by referring to the Maugin condition.[7,8]

STATIC PERFORMANCE OF TN AND GH LCD'S[9,10]

The liquid crystal used for a TN mode is E-7 (E. Merck) and that for a GH mode is E-18 (E. Merck). These materials have a positive dielectric anisotropy. The dye is of the anthraquinone type, D-16 (E. Merck) and the concentration is 1 wt%. The thickness of a TN cell is about 9 μm and that of a GH cell is about 18 μm. The GH cell is operated in a negative type display. The waveform of applied voltage is a sine wave at a frequency of 1 KHz.

Figures 12 and 13 illustrate the lightness L^* against applied voltage V and the transmittance T against applied voltage V, which are characteristics of a TN cell with the neutral gray and bluish-gray polarizers. The closed square points are experimental values of the conventional T-V character-

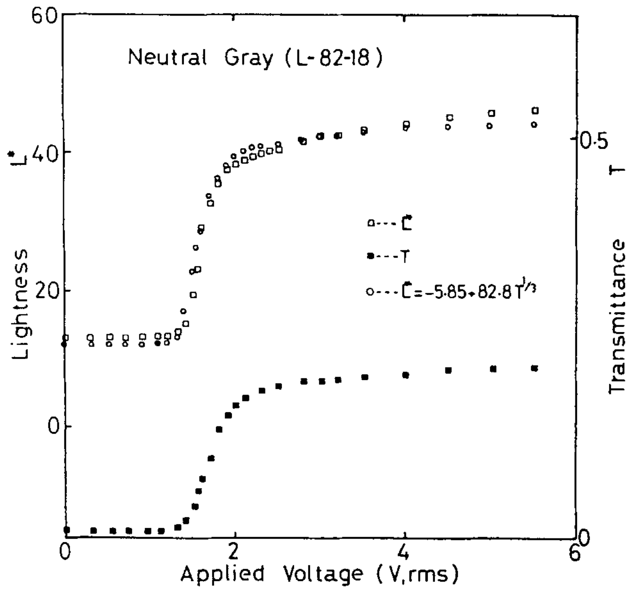

FIGURE 12 Lightness and transmittance vs applied voltage for a TN cell with the neutral gray polarizers.

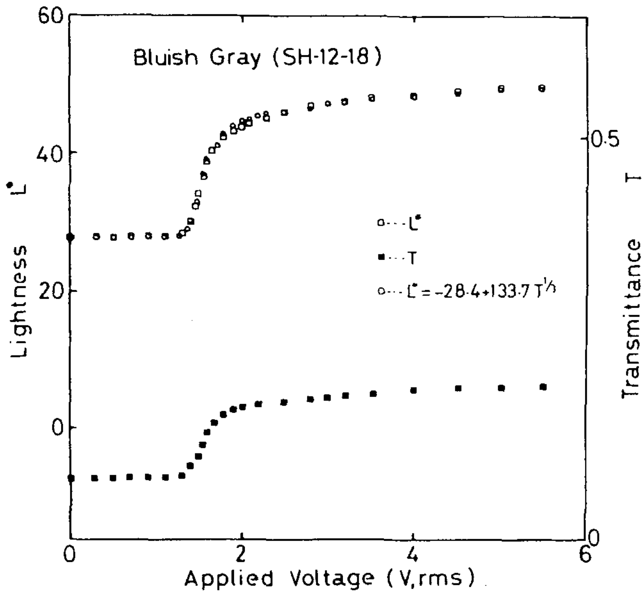

FIGURE 13 Lightness and transmittance vs applied voltage for a TN cell with the bluish-gray polarizers.

istics, and the open square points are the L^*-V characteristics. Each closed square point is translated to the open circle points at the same voltage by cube root functions: $L^* = -5.85 + 82.8T^{1/3}$ corresponds to the neutral gray polarizer, and $L^* = -24.8 + 133.7T^{1/3}$ to the bluish-gray polarizer.

In order to determine these functions, we applied to a least squares method mentioned above two kinds of functions. The translated points from T to L^* agree better with the experimental values of L^* by a cube root function other than the logarithmic one. This means that the transmittance is a cube root function with respect to the perception of the human eye for both LCDs. Compared to the threshold sharpness of the L^*-V and the T-V characteristic curves, it is obvious that the sharpness of the L^*-V curve is steeper than that of the T-V curve for Figures 12 and 13.

Figure 14 shows the color difference ΔE^* against the contrast ratio C characteristics of TN LCDs for both polarizers. The maximum values ΔE^* and C are about 38 and 23 for the neutral gray polarizer, and 38 and 2.5 for the bluish-gray polarizer. This fact means that color differences both for neutral gray and bluish-gray polarizers are almost the same, whereas the contrast ratio for the bluish-gray polarizer is very small compared with the neutral gray polarizer. Actually, we cannot recognize such a large differ-

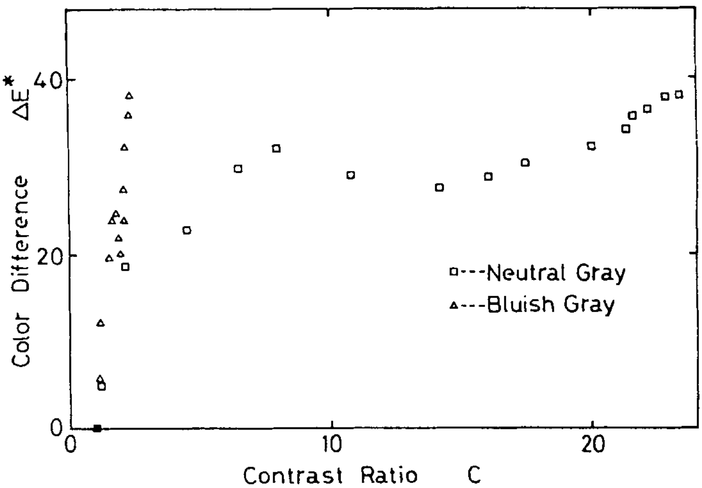

FIGURE 14 Color difference vs contrast ratio characteristic of TN LCDs with neutral gray and bluish-gray polarizers.

ence as indicated by the values of the contrast ratio. Thus the color difference is more useful for estimating the performance of the LCD operated in various modes.

We further compared the relation between the color difference and the applied voltage for TN and GH mode LCDs. Figure 15 shows the result.

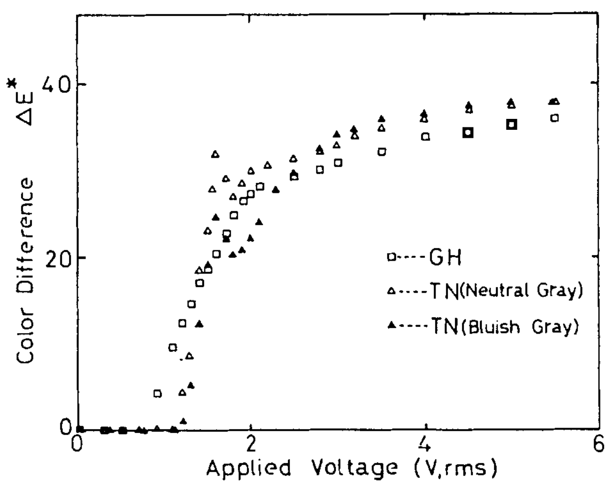

FIGURE 15 Color difference vs applied voltage characteristic of TN and GH cells.

According to the Figure 15, color occurs near 1.8V in the TN cells, but it does not occur in the GH cells. This color is caused by the influence of the birefringence of the TN cell. Comparing the maximum values of the color difference, we find a significant color difference between the TN and GH mode LCDs; thus, we can estimate the performance of the TN and GH mode displays unifiedly by considering the colorimetric quantity ΔE^*.

Obtaining a good contrast from non-emissive displays such as LCDs is done at the cost of lightness or whiteness of the nearly colorless part of the monocolor displays. Therefore, there is a trade-off for getting good legibility between the color difference and the lightness or whiteness. A simple example of this procedure is a comparison between the parallel and crossed states of a pair of polarizers by changing their dichroism. This result is shown in Figure 16. From this result, we have made an evaluation and optimization of polarizers, which are made from conventional iodine molecules and developed dye stuffs. Optimum concentration of dyes for GH LCDs is also determined and a black dye is designed and evaluated in this way.

The static performance of transmissive TN LCDs with developed polarizers and the optimized GH LCDs without a polarizer (and double-layered ones[11]) have been examined colorimetrically. A plot of the color difference

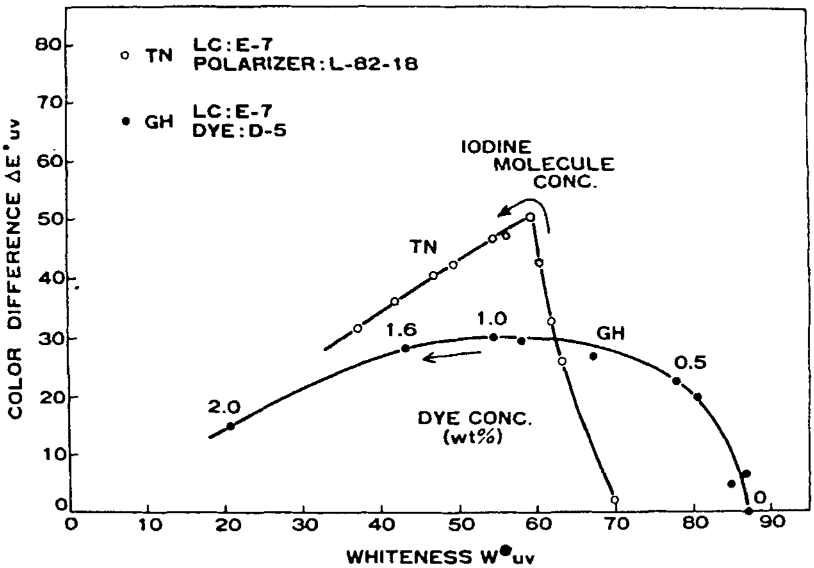

FIGURE 16 Color difference vs whiteness for a comparison between the parallel and crossed states of a pair of polarizers by changing their dichroism.

between crossed and parallel states of a pair of polarizers against the whiteness of the parallel state gives a broad peak if the dichroism of each polarizer is changed systematically. The value of the dichroism giving the peak in this plot is an optimized one. The same is true for the optimum concentration of dye stuff of a GH cell.

We examined over 50 different kinds of polarizers and some black dyes composed of some components. Some TN and GH LCDs with the optimized above-mentioned materials are shown in Figure 17. As it can be seen, TN cells with polarizers in an L-12-18 : L-12-18 combination and in an L-82-18 : L-82-18 combination are superior to others in both the color difference between the ON and OFF states and in the whiteness of the colorless part. An optimized double-layered GH cell with blue dye (D-5) is comparable to some TN cells in its color difference but inferior to them in whiteness. The same is true for a black dye GH cell. In this way, we succeeded in getting a way of comparing different kinds of LCDs standing on the same basis.

Ergonomic evaluation was done based on the magnitude method developed by Scheffe.[12] The evaluation was done by ten observers comparing two square samples of 50 × 50 mm^2 area having a hollow circle with a diameter of 10 mm in the center of each sample, one of which is switched on and the other off. The experimental apparatus is shown in Figure 18.

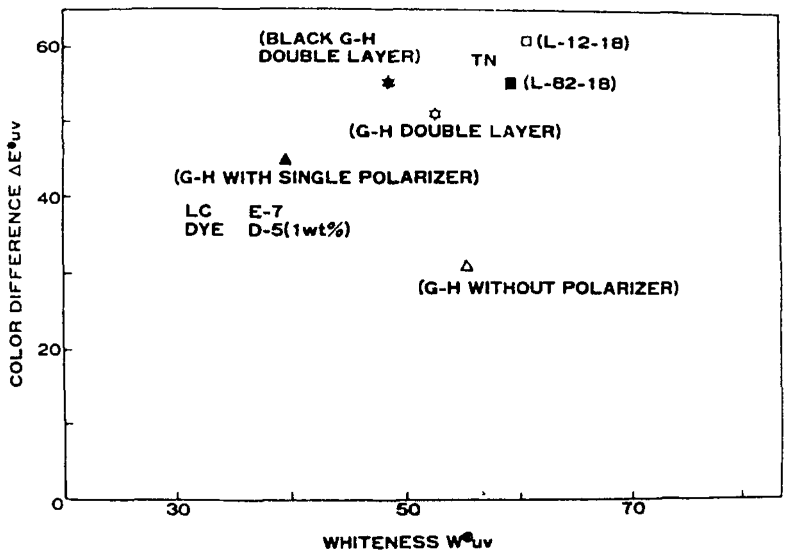

FIGURE 17 Color difference (ON state and OFF state) vs whiteness of colorless part of TN and GH LCDs.

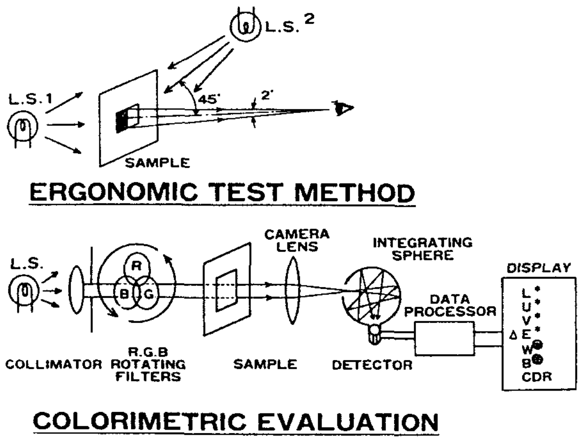

FIGURE 18 Ergonomic test method and colorimetric evaluation.

Table III shows the results of the colorimetric and ergonomic evaluation of TN cells with developed polarizers. Sample A has the highest value of the color difference. The order of the samples from A to D is aligned according to the order of their value of color difference.

We think that the color difference will be the most important aspect in considering the merits of both achromatic and color LCDs, and that LCDs having a color difference of above 50, as determined by our measuring system, will be acceptable for practical use. We know of about 10 polarizers which pass this test. As it is seen in Table III, sample A has a slightly larger value of color difference compared with sample B but the former gives a fairly larger ergonomical preference. This trend can be explained by taking account of the favoritism on the blue trace existing in the colorless part of sample A. The color difference ratio given in this article is defined

TABLE III

Colorimetric and ergonomic test data of TN cells with developed polarizers

Sample	A	B	C	D
Polarizers	L-12-18	CR-18	CA-18	CG-18
Combination	+)L-12-18	+)L-82-18	+)L-82-18	+)L-82-18
Hue	Blue	Red	Umber	Green
Color difference ΔE^*uv	60	59	47	38
Whiteness W^{*}uv	61	59	54	56
Relative preference	+1.23	+0.05	−0.55	−0.73
Color difference ratio CDR	1.54	1.44	1.02	0.86

by taking account of the whiteness. CDR shows a better correlation with preference over others. The samples C and D are not acceptable because of their inferiority in color difference. The above-mentioned evaluation method cannot be applied directly to dual-color displays.

COLOR GAMUT[13]

The color gamut of the color television receiver phosphors (CTRP), or color photographic film (CPF), has already been reported.[14] However, the color gamut of LCDs is not revealed. In this article we investigate the quantitative color gamut of TB and GH modes LCDs under ambient illumination.

Procedures to obtain the color gamut are as follows: (1) confirm the validity of the matrix representation method[15] used to calculate the color matching between given chromaticity coordinates and those calculated at the constant lightness of the ambient illumination; (2) confirm this analytical method in the colorimetric experiment; (3) decide the color gamut under the ambient illumination by the same analytical method.

In the matrix representation method we deal with a TN mode with dichroic polarizers in the same manner as a GH mode to simplify the calculation, because the color in a TN mode with dichroic polarizers depends on the dichroism of a dye in the same way in a GH mode.

The ULCS diagram (U^*, V^*, W^*) was used to evaluate the color difference, including the lightness scale. It is proposed to modify the scale for display usage so that W^* is related to the conventional display gray scale:

$$W^* = (\log Y + 4 \log 10)/\log\sqrt{2} = 6.6439(\log Y + 4), \qquad (13)$$

where Y is the lightness. This combined lightness and chromaticity scale is applicable to an environment wherein the ambient illumination is at least one gray level below the lowest display illuminance.

Doucette[16] modified Eq. (13) for a reflection-type digital display by taking account of the effect of the higher level of ambient illumination and recommended the following modification to the 1964 CIE system:

$$W^* = 6.6439(\log Y + 4) - (\log Y_a + 4), \qquad (14)$$

$$U^* = 13W^*(u - u_0), \qquad (15)$$

$$V^* = 19.5W^*(v - v_0), \qquad (16)$$

where Y_a is the lightness of the ambient illumination. We further modified Eq. (14) for a transmissive-type LCD as follows:

$$W^* = 6.6439(\log Y + 4) - 3 \log Y_a \tag{17}$$

The matrix representation method is an approximation where only the linear terms of Taylor's series expansion of U^*, V^*, W^* can be expressed in a matrix representation:

$$\begin{bmatrix} \Delta U^* \\ \Delta V^* \\ \Delta W^* \end{bmatrix} = \begin{bmatrix} \frac{\partial U^*}{\partial \alpha} & \frac{\partial U^*}{\partial \beta} & \frac{\partial U^*}{\partial \gamma} \\ \frac{\partial V^*}{\partial \alpha} & \frac{\partial V^*}{\partial \beta} & \frac{\partial V^*}{\partial \gamma} \\ \frac{\partial W^*}{\partial \alpha} & \frac{\partial W^*}{\partial \beta} & \frac{\partial W^*}{\partial \gamma} \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta \beta \\ \Delta \gamma \end{bmatrix} = [\mathrm{J}] \begin{bmatrix} \Delta \alpha \\ \Delta \beta \\ \Delta \gamma \end{bmatrix}, \tag{18}$$

where α, β, γ correspond to the voltage V_i ($i = A, B, C$), to the cell in the TB mode, or to the dye amount a, b, c in the GH mode.

By multiplexing the inverse matrix from the left-hand side of Eq. (18), we can write $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$ as follows:

$$\begin{bmatrix} \Delta \alpha \\ \Delta \beta \\ \Delta \gamma \end{bmatrix} = [\mathrm{J}]^{-1} \begin{bmatrix} \Delta U^* \\ \Delta V^* \\ \Delta W^* \end{bmatrix} \tag{19}$$

Thus, the small change of α, β, γ resulting from small changes of trichromatic specifications U^*, V^*, W^* can be computed from Eq. (19). The elements of the inverse matrix can be computed by referring to Eqs. (15)–(17). Finally, partial derivatives of U^*, V^*, W^* are done with respect to α, β, γ.

The optical percentage transmittance in the TB and GH modes is shown as:

TB mode:[17] $$T = 100 \sin^2 \pi \cdot d \cdot \Delta n / \lambda, \tag{20}$$

GH mode:[18] $$T = 10^2 - (aD_a + bD_b + cD_c), \tag{21}$$

where d is the thickness of the liquid crystal layer, Δn is the effective refractive birefringence, and D_i ($i = a, b, c$) are the spectral density distribution of the dyes per unit amount.

From these procedures the element of the inverse matrix can be computed, and the value of the voltage applied to the cell in the TB mode or in the value of the dye amount of the cell in the GH mode can be obtained.

The liquid crystal used in the TB mode is a mixture of MBBA and BBCA (butoxybenzylidene-cyanoaniline) 4:1 by weight. The cell thickness is 24 μm. The cell is placed between crossed polarizers at 45° relative to the directors of the molecules of the liquid crystal. In the GH mode a polarizer is used. The guest material is merocyanine dye[19] and that used as the host is a mixture of cholesteryl chloride and the same nematic liquid crystal mentioned above. Measurement was done with a cell showing Grandjean texture. In this experiment, Eq. (21) applies in sufficiently large pitch. The pitch was measured by a Cano wedge arrangement[20] with a cathetometer and was 16 μm of a 2% concentration of cholesteryl chloride. The applicability of Eq. (21) to this pitch was confirmed. The cell thickness is 25 μm. Orientation treatment was made with the oblique evaporation 85° normal to the electrode of SiO.

An example of the computer output data is shown in Table IV. Table IV corresponds to the case of Y_a = 40%, and the symbols NK-1247, NK-1321 and NK-1575 in the GH mode stand for the three kinds of merocyanine dye.

To confirm the validity of the analytical method, a colorimetric experiment was carried out. Figure 19 shows the optical apparatus: light source S_1 is the CIE standard illuminant B(4870 K); light source S_2 is the CIE standard illuminant B or illuminant C(6740 K) used for the ambient illumination. The direction of the incident light of the light source S_2 is 45° relative to the optic axis of the apparatus. The colorimetric data are shown in Table V. In Table V experimental data for ambient illumination of the CIE standard illuminant B are in good agreement with the computed data with the defined tolerable color difference, but they do not always agree with the computed data for ambient illumination of the CIE standard illuminant C. These results show that Eq. (17) only applies to the ambient illumination of light source S_2 having the same chromaticity as the reference illumination of light source S_1. For this reason, we define light source S_1 as being identical to light source S_2, or light source S_1 is the CIE standard illuminant B.

TABLE IV

Computer output of color matching at Y_a = 40%

Given values	
$u = 0.15$, $v = 0.25$, $Y = 10.0$, $U^* = 21.5$, $V^* = -37.7$, $W^* = 27.6$, Color temperature = 4870 Kelvin, Limit iteration = 100, Tolerable color difference: $\Delta E^* = 10.0$	
Calculated values	
TB mode:	$u = 0.157$, $v = 0.263$, $Y = 10.3$, $U^* = -21.1$, $V^* = -33.6$, $W^* = 28.5$, $v_A = 1.3$, $v_B = 2.4$, $v_C = 5.6$(V,rms), $\Delta E^* = 4.22$
GH mode:	$u = 0.165$, $v = 0.244$, $Y = 9.6$, $U^* = -17.90$, $V^* = -43.9$, $W^* = 28.3$, a(NK-1247) = 0.05, b(NK-1575) = 0.28, c(NK-1321) = 0.22(wt %), $\Delta E^* = 7.2$

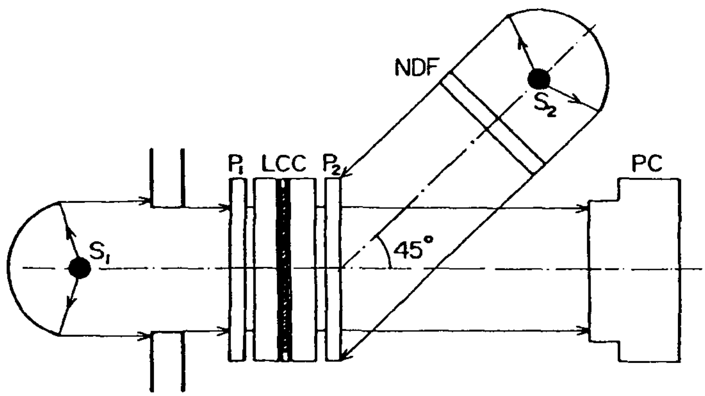

FIGURE 19 Optical apparatus: $S_i(i = 1,2)$, light source; $P_i(i = 1,2)$, polarizer; LCC, liquid crystal cell; PC, photoelectric colorimeter; NDF, neutral density filter.

The color gamut of a nematic LCD under ambient illumination can be determined by examining the existence of applied voltage or dye amounts corresponding to the given chromaticity coordinates (U^*, V^*, W^*) and the lightness Y_a of the ambient illumination, because the color gamut is determined directly by a matrix representation method. The color gamut shown on the chromaticity diagram is a projection of the color solid in the color space. The color solid is formed by calculating the various values of chromaticity coordinates at the given lightness of the ambient illumination.

Figures 20–23 are examples of the color gamut in the TB or GH mode. The solid and oblique lines stand for the color gamut of the nematic LCD

TABLE V

Colorimetric data of color matching at $Y_a = 40\%$

A light source S_2: the CIE standard illuminant *C*	
TB mode:	$u = 0.11$, $v = 0.22$, $Y = 12.4$, $U^* = -33.16$, $V^* = -51.70$, $W^* = 29.03$, $\Delta E^* = 21.75$
GH mode:	$u = 0.19$, $v = 0.20$, $Y = 13.5$, $U^* = -4.51$, $V^* = -64.13$, $W^* = 29.28$, $\Delta E^* = 24.28$
A light source S_2: the CIE standard illuminant *B*	
TB mode:	$u = 0.17$, $v = 0.26$, $Y = 9.8$, $U^* = -14.99$, $V^* = -35.67$, $W^* = 28.36$, $\Delta E^* = 6.50$
GH mode:	$u = 0.18$, $v = 0.23$, $Y = 9.1$, $U^* = -12.68$, $V^* = -49.66$, $W^* = 28.14$, $\Delta E^* = 7.78$

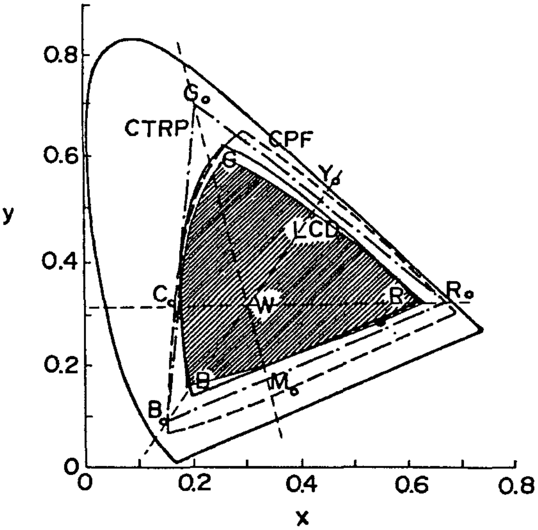

FIGURE 20 CIE chromaticity diagram of TB mode. The solid and oblique lines represent the color gamut of a nematic LCD at lightness Y_a = 1% and Y_a = 40%; The dot-dash line represents the gamut of CTRP; the dashed line stands for the gamut of CPF.

at lightness $Y_a = 1\%$ and $Y_a = 40\%$. The dot-dash line stands for the gamut of CTRP; the dashed line stands for the color gamut of CPF.

In Figures 20 and 22 three dashed lines through source point W indicate the intersections of planes normal to the chromaticity diagram through the TV receiver primary points. The symbols R_o, G_o, B_o, C_o, M_o, and Y_o stand

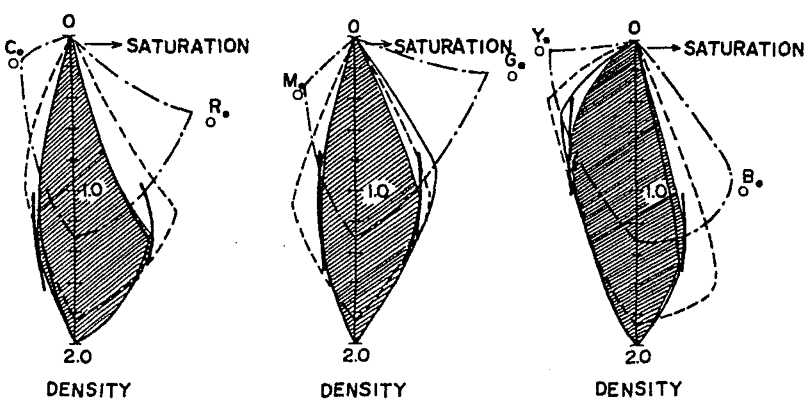

FIGURE 21 Color solid of TB mode. The ordinate and abscissa of the color solid represent the equivalent neutral density of CPF and the saturation. The wide solid line stands for the envelope line of the maximum saturation at the variation of lightness.

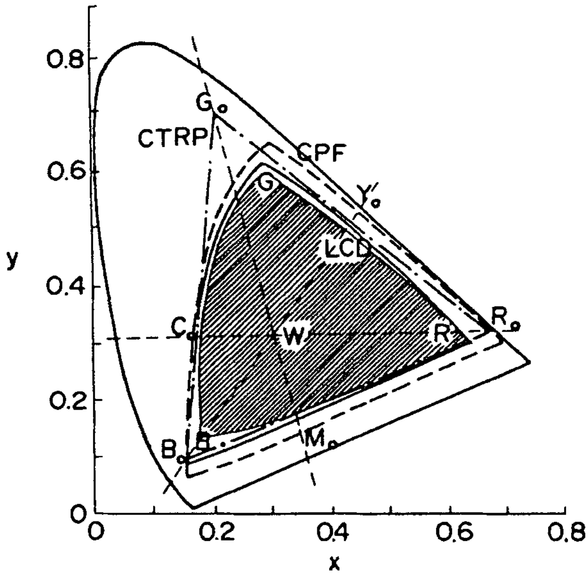

FIGURE 22 CIE chromaticity diagram of GH mode. The lines stand for the gamut similar to those in Figure 20.

for the red, green, blue, cyan, magenta and yellow in CTRP, and the symbols *R*, *G*, *B* stand for the red, green and blue in the nematic LCD at lightness $Y_a = 1\%$.

Figures 21 and 23 show the cross sections of the color solid corresponding to the lines marked G_o-M_o,R_o-C_o, and B_o-Y_o in Figure 20 or 22. The

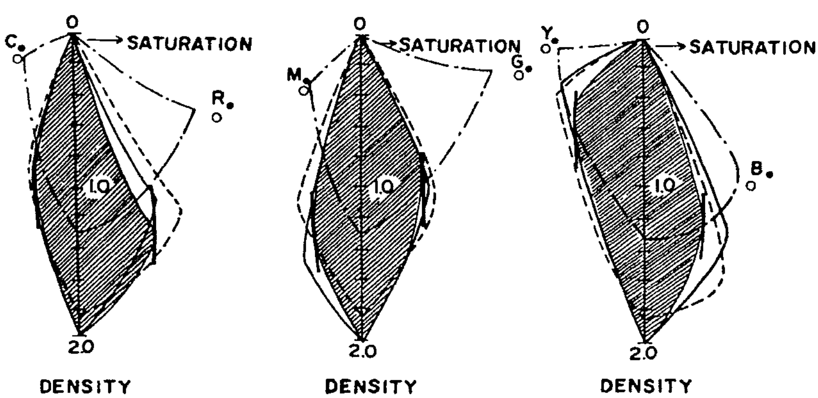

FIGURE 23 Color solid of GH mode. The ordinate and abscissa of the color solid and the wide line have the same meaning as in Figure 21.

intuitive colorimetric properties of display elements can be depicted conveniently with the color solid. The ordinate stands for the equivalent neutral density of CPF, i.e. the lightness scale of the 1964 CIE chromaticity diagram is converted to the scale of the equivalent neutral density of passive-type CPF similar to the LCD. The abscissa indicates saturation. The wide solid line stands for the envelope line of maximum saturation at the variation of lightness Y_a.

The curve of the color gamut in the CIE chromaticity diagram is caused by the convex shape of the color solid. The zero density at the top of the ordinate is equal to the maximum luminance. The 2.0 density at the bottom of the ordinate is equal to the minimum luminance. The abscissa is proportional to the distance in the chromaticity diagram between the source point W and the LCD primary point. Increasing the distance from the ordinate indicates increasing the saturation.

From Figures 20 and 22 the saturation of red in $Y_a = 40\%$ is higher than that in $Y_a = 1\%$. Unlike red, the saturation of green or blue in $Y_a = 40\%$ is lower than that in $Y_a = 1\%$, because of the spectral characteristic of illuminant B used for ambient illumination. From Figures 21 and 23 the degree of modification of the color solid in the GH mode is larger than that in the TB mode. This discrepancy is due to the difference of color properties of each mode or the color of the TB mode is essentially equal to the thin film interference color, and the color of the GH mode is equal to the color based on the dichroism of the dye. This tendency is the same as the other lightness of ambient illumination.

CONCLUSION

The colorimetric method is useful for evaluating and optimizing LCDs. The color difference of a practical polarizer is a logarithmic function of the contrast ratio for the neutral gray polarizer, but not for the bluish-gray one. The lightness of TN LCDs for the neutral gray and bluish-gray polarizer is a cube root function of the light transmittance for the white light.

In the multiplexed LCDs, the number of scanned lines was obtained by colorimetry. Color as well as multiplexability is strongly dependent on the nature of the polarizer.

The definition of CDR shows a good correlation with the ergonomic test. But since the colorimetric method is more sensitive to the variation of the conditions of the sample more than with the physical method, there is need for the calibration of the instrument.

Further, the theoretical color gamut of a nematic LCD under ambient illumination is revealed. Calculated data for ambient illumination having the same chromaticity as the reference illumination are in good agreement with the colorimetric data within a tolerable color difference.

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