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〈Research Paper〉

Correction of CIEDE2000 Color Difference Formula for the Analysis of Low Chroma and Low Lightness Colors

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Abstract— There are many discrepancies between visually perceived color-difference and that which is quantified from an instrumental measurement when dark color samples are measured in the textile industry. The samples were prepared to represent these dark shades and the values of the instrumental results from conventional color-difference formulae(CIELAB, CMC, BFDⅡ, CIE94, LCD99 and CIEDE2000). Those of visual assessment were compared. The experimental results show that the CIELAB formula gives the best performance over other formulae, and the CIEDE2000 formula for the color-difference according to chroma presents the worst performance. Therefore, we can say that the problems in color matching of dark shades are caused by imperfect formula, because the results obtained from a color-difference formulae are different and the CMC which is used as a standard color-difference formula in the textile industry is not correct. So, a revised color-difference formula is proposed in this study, to account for these problems.

Keywords: *the dark region, chroma, color-difference formula, CIELAB, CIEDE2000*

1. Introduction

The measurements of color-difference have long been a subject of interest to the color scientists. The aim of a color-difference formula is to give a close correlation between the visually perceived color-difference and that which is quantified from an instrumental measurement. Industrial color-difference evaluation has been one of the main topics in the field of color science and technology for more than three decades.

Color-difference formulae have been developed in association with the progress of color vision theories and uniform color spaces. Some formulae progress from a purely empirical approach. They can be divided into three groups according to their methodology and history: a) formulae based on the Munsell system, b) formulae based on the empirical approach, c) formulae based on the theoretical approach. This classification couldn't be, of course, absolute. Some have both aspects of empirical and theoretical approaches, i.e., a composite or hybrid type. The principal trend of recent advanced color-difference formulae is that the color-difference is evaluated by weighted ΔL^*, ΔC^* and ΔH^* values[1-2]. Currently the advanced formulae have large discrepancies among themselves, as well as other shortcomings.

First, they have different methods for predicting lightness differences. The S_L functions of CMC and BFD agree reasonably well, but they disagree with the L^* scale used in the CIE94 formula. Second, they have different methods for predicting hue differences. The CIE94 and LCD formula have hue weighting functions, S_H, which are independent of a hue angle. Furthermore, the hue-dependent functions for the BFD and CMC formula are quite different. Third, the CMC and CIE94 formula

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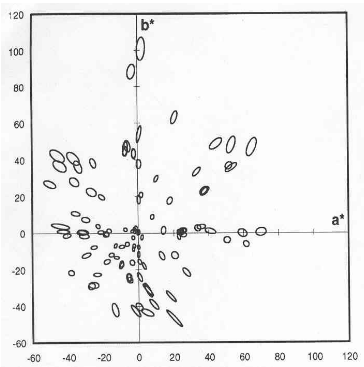
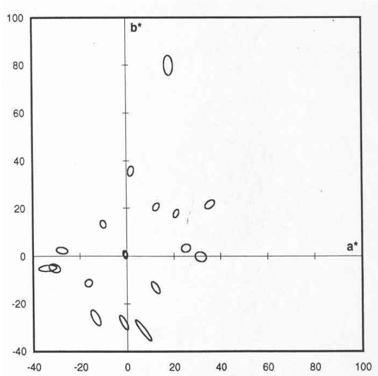
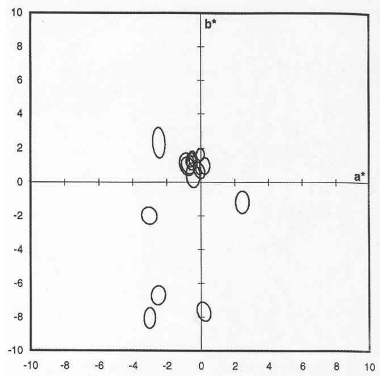


(a) Luo and Rigg experimental color discrimination ellipses plotted in a*b*diagram.



(b) RIT-DuPont color discrimination ellipses plotted in a*b* diagram.



(c) Experimental ellipses close to the neutral axis plotted in a*b*diagram. The BFD, Leeds, RIT-DuPont, and Witt ellipses are plotted in black, red, green, and pink colors, respectively.

Fig. 1. The variation of acceptable color tolerances.

exhibit large errors in predicting chromatic differences for saturated blue colors, while the BFD and LCD formula do not.

Fig. 1(a) and 1(b) show that all tolerance ellipses in the blue region(particularly around a = 10, b = -40) do not point towards the origin. This disagrees with what is predicted by the CMC and CIE94 formula. This is the reason why a function is required to rotate these ellipses as included in the BFD and LCD formula. Finally, all formulae incorrectly predict chromatic differences among neutral colors, as the chromatic ellipses from experimental data sets are oriented towards 90°, not constant-diameter circles as implied by all the advanced formulae. This can be seen in Fig. 1(c), which includes all ellipses close to the neutral axis derived from the BFD, Leeds, RIT-DuPont, and Witt data sets[3].

The goal of this study is to examine the agreement among the color-difference formulae in the textile industry. For this, the performances of conventional advanced CIELAB formulae(CMC, BFDⅡ, CIE94, DCI95, LCD97, LCD99, and CIEDE2000) are compared. A data set prepared in the dark region, which gives problems, was investigated to obtain the correlation between visual scales and colorimetric magnitudes. The color discrimination threshold ranged from small to medium color-difference(mean CIELAB $\Delta E < 5.0$) in the dark region. BFDⅡ was used in this study, because the BFDⅡ formula is superior in performance to BFD. Also, a revised color-difference formula based on these results is proposed.

2. Experimental

2.1. Sample pair preparation and color measurement

The experiments were carried out under a D65 simulator in a light booth. The samples were prepared to correspond to dark color by applying disperse dyes onto polyester fabric. The fabric was a left twill (bright) of 108×105. Each sample had a physical size of 5×6.5 square centimeter. The CIELAB coordinates of the samples were measured using the X-Rite8200 spectrophotometer. The colorimetric values were calculated under the CIE D65 Illuminant and 1964 standard colorimetric observer.

2.2. Color-difference measurement

A total of 491 pairs were assessed by a panel of 50 observers in all phases. All observers were undergraduate students at Yeungnam University.

They had little experiences in scaling the color-difference. Each pair was assessed against a grade prepared in this study. The observers were asked to compare the color-difference of a test pair with those of a prepared grade and to choose the closest grade. The observers were encouraged to give intermediate grades with up to 1 decimal place. These grades were similar to the standard gray scales used in fastness testing for assessing color change in the textile industry. The CIELAB $L^*a^*b^*$ values for each grade and standard under CIE D65 illuminant and 1964 standard colorimetric observer are given in Table 1 together with ΔL^* and ΔE values calculated between each grade and the standard. The results show that the ΔL^* values closely agree with the ΔE values. This indicates that all differences were essentially lightness differences. The gray scale method used for visual assessment was identical to that used by Luo and Rigg[4] and Kuo and Luo[5-6].

Table 1. The grades for visual assessment

Grade	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE
1.00	48.69	0.02	-0.55	0.99	0.13	0.02	1.00
2.00	49.74	0.93	-4.7	1.81	0.85	0.02	2.00
3.05	49.84	0.52	-4.64	2.97	0.71	0.01	3.05
4.71	47.97	-0.45	-1.11	4.70	-0.04	-0.24	4.71
7.05	50.24	0.30	-5.50	7.04	0.38	0.06	7.05
9.65	52.92	-0.12	-0.84	9.65	0.29	0.03	9.65

3. Results and Discussion

3.1. Evaluating the performance of color-difference formulae

Performance Factor (*PF*) has been widely used by previous researchers as an indicator for observer accuracy and the performance of color-difference formulae in comparison with visual results[7,8,12]. A *PF* combines with several measures of fit: Gamma factor γ, coefficient of variation of E, CV, V_{AB}, and the correlation coefficient of ΔE and ΔVr[4,13]. In this study, correlation coefficient r is not included in the performance factor. Only the first three measures are used, i.e., $PF'/3$ is adopted, which is given by Eq. (1).

$$PF'/3 = 100[(\gamma - 1) + V_{AB} + CV/100]/3 \quad (1)$$

For a perfect agreement between the ΔE values predicted by a particular equation and visual results, ΔV, $PF'/3$ should be equal to zero. For example, a $PF/3$ of 30 indicates a disagreement of about 30%.

The $PF/3$ values calculated from various color-difference formulae are given in Fig. 2. In the calculation of the $PF/3$, ΔV was adjusted by a scaling factor onto the same scale as the ΔE values were calculated from a color-difference formula[7-8]. The scaling factor was calculated using the least square method between ΔV and ΔE. This testing method does not consider the parametric effect from the visual data. The fit of each formula with the l value(l: relative tolerance of lightness) of 1 and 2 is tested because the l values recommended for the textile samples with each formula are all different. It is noted that the CIELAB formula performs best among all color-difference formulae. The CIE94 formula is the best fit, followed by DCI95, LCD97 and LCD 99. CIEDE2000 is the least fit. It is thought that CIEDE2000 was made by samples of only 5 centers, according to chroma. The $PF'/3$ value has a merit in that it is easy to compare, while it is difficult to judge how good the agreement is.

As an alternative measure, the plots of ΔE versus ΔV are given in Fig. 3, which shows the agreement of the calculated data with the visual data acquired from the experiment. The CIELAB data shows more convergent on the 1:1 line of instrumental and visual assessment than those from other formulae. While CIEDE2000 has the least correlation coefficient(0.92) between E and V, indicating that these it is disagreeing between E and V. CIE94 has a pattern similar to LCD97 and LCD99, but the points of LCD99 converge on the 1:1 line. CIEDE2000 data shows relatively greater disagreement at low chroma color-difference, which is caused by very few samples.

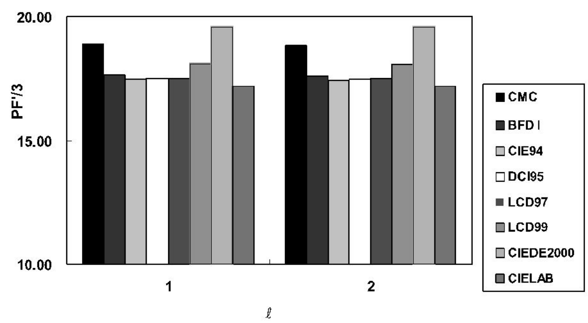


Fig. 2. The performance of the color-difference formulae.

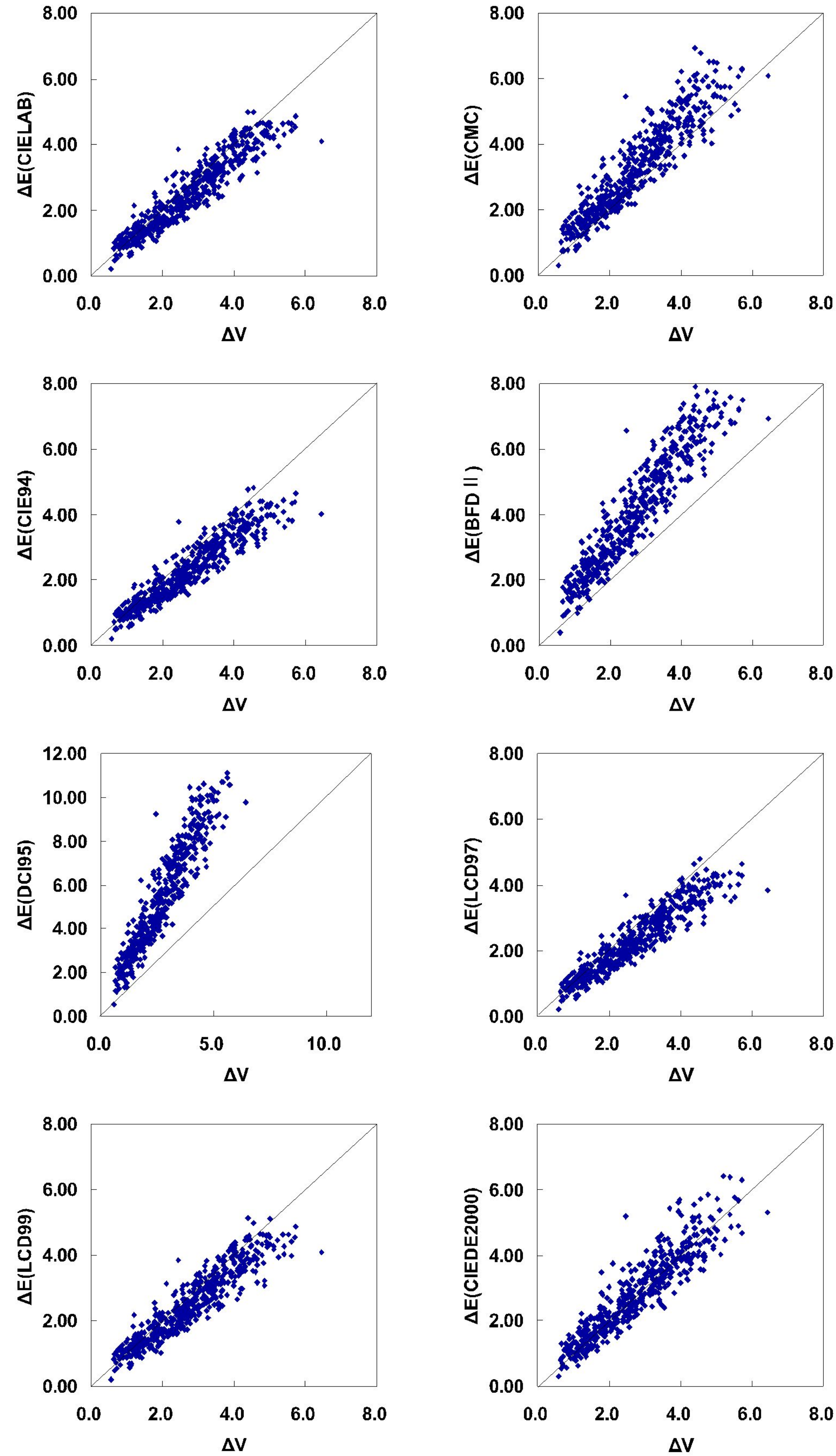


Fig. 3. Plots of ΔE versus ΔV for all visual data (l=2).

This study used 2 of l that is similarly used in the textile industry. Figures are shown below that indicate there is seldom a performance difference due to the change in relative tolerance of lightness at the low chroma region because human eyes are insensitive to this lightness.

3.2. Error of Color Measurement

It is very important to take into consideration the errors of measurement in color measurement. To estimate errors in color measurement, both of the DIN and ASTM methods[14] require more than 10 repeated measurements. Since it is impractical to quantify theoverall measurement error of 491 color-difference pairs, a simpler method is used[18] in this study. Table 2 shows the error of color measurement. It is calculated from the errors of 20 pairs selected from all the pairs. The standard deviation of the total and the components of color-difference is less than 0.12, namely around the 0.1 ΔE* unit. The CV(%) for the total color-difference(ΔE*) is 48%. Concerning the established research for the precision of color measurement, it is established that the means of color-difference from the mean of a set of measurements(5 replications) were less than 0.1 CIELAB unit and the coefficients of variation(CV) of three repeated color-difference measurements were below 2.7~8.9%. This indicates that the precision of this study is acceptable and samples do not change appreciably during the experiments.

3.3. Observer uncertainty

The precision of visual assessments is given in Table 3. The overall standard error is ±6.22%. Considering that it is difficult to decide the grade of glossy textile pairs and that the precision of Luo and the Bern's data sets is ±8.9% and ±5.7%, respectively[18], the visual assessments are thought to be reasonably performed under well-controlled conditions. The overall mean and the standard deviation of grade scale values for 50 assessments are 4.80 and 0.18, respectively. Thus, the standard deviation of the mean grade scale values is $0.025 = \frac{0.18}{\sqrt{50}}$. That is, if all the experiments are

Table 2. Precision of instrumental color-difference measurement

	S.D.*	Mean	CV(%)
ΔE*	0.12	2.50	4.80
ΔL*	0.6	0.09	66.70
Δa*	1.02	1.42	71.80
Δb*	1.15	1.75	66.86

*S.D.: Standard Deviation.

Table 3. Precision(standard error) of visual assessments

	Mean	S.D.	S.D. of MGS*	$-1\sigma/\sqrt{n}$	$1\sigma/\sqrt{n}$	Standard Error
GS	4.8	0.18	**0.025**	4.78	4.83	
ΔV	2.8	0.44		2.26	3.14	**0.0622**

*MGS: Mean Grade Scale value.

repeated several times for a typical pair, 68% of the mean grade scale values should fall within ±0.025 of the true mean. For a grade scale value of 4.80, the lower and upper 68% confidence limits (1σ limit) are 4.78 and 4.83. These limits are converted to ΔV values using the equation of related grade scale and ΔV, yielding 2.26 and 3.14. The standard deviation is 0.44 with 50 repeated visual assessments and finally, the precision (standard error) is $6.22(\%) = \frac{0.44}{\sqrt{50}} \times 100$

3.4. The a′ factor adjustment in CIEDE2000

CIEDE2000 color-difference formula is revised for dark color assessment in this study because the color-difference formula has many errors in the dark color region when the formula is compared with the visual assessment. Fig. 4 shows that the color tolerances of instrumental and visual assessment are different. When the instrumental color-difference(ΔE) and visual assessment(ΔV) were 1, ΔV has a longer axis ellipsoid than that of ΔE.

Fig. 5 shows that the difference in color tolerance between ΔE and ΔV has some tendency to accumulate in the a*b* plane. Generally, color tolerance is ellipsoidal having a longer axis at low chroma. However, color tolerance tends to be more circular for increasing chroma.

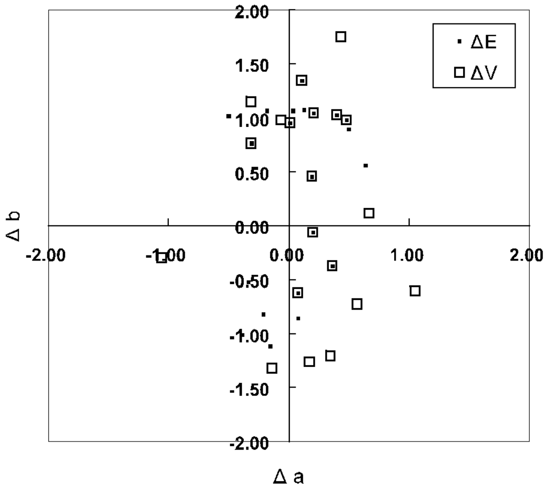


Fig. 4. Comparison with color tolerances of ΔE and ΔV below color-difference of 1.

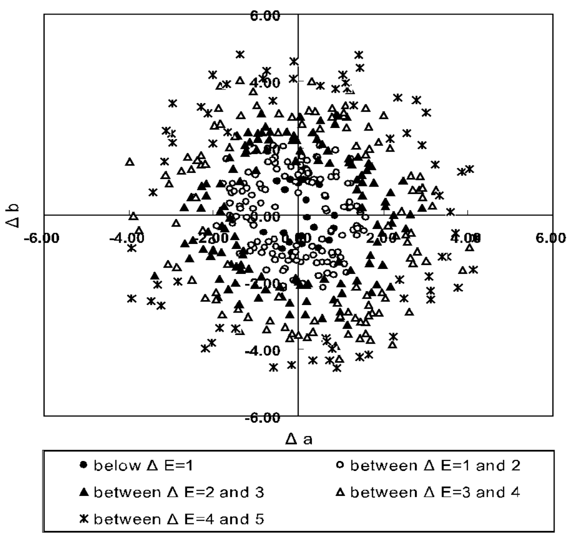


Fig. 5. Color tolerances according to chroma in a*b* plane.

The CIEDE2000 color-difference formula is revised for this point. Though it is the latest recommended formula for different chroma, it has some discrepancies when it is compared to the visual assessment of the same samples in this study. To solve this problem, a′ of CIEDE2000 is revised. Also, the G factor(equation) in CIEDE2000, having color tolerance according to chroma, is revised as in Fig. 6 and 7. Therefore, the performance of the formula is noted by the change in an exponent of chroma and a constant in the G equation. The result shows the best performance value (PF′/3 is 16.46) with an exponent of 0.05. As shown in Fig. 7, PF shows the smallest value of 16.42 when the G equation coefficient is between 0.12 and 0.13. The PF value is equal at the two spots, however, the values of CV are respectively 14.02 and 14.03. A more corrective formula is obtained when the coefficient is 0.12. It appears that the color tolerance of the color-difference formula with revised a′ is a rounder ellipsoid than the color tolerance of CIEDE2000 and revised CIEDE2000, shown in Fig. 8. Table 4 shows the comparison of the fit between conventional color-difference formulae and the new a′ for data set(l=2). The new formula with a′ is more accurate than other formulae with respect to CV PF′/3, PF/4, etc.

$$a' = (1+G)a^* \qquad G = 0.5\left(1-\sqrt{\frac{\overline{C^*_{ab}}^{\,7}}{\overline{C^*_{ab}}^{\,7}+25^7}}\right)$$

$$\overline{C^*_{ab}}^{\,7} : average\ of\ sample\ pair'\ C^*_{ab}$$

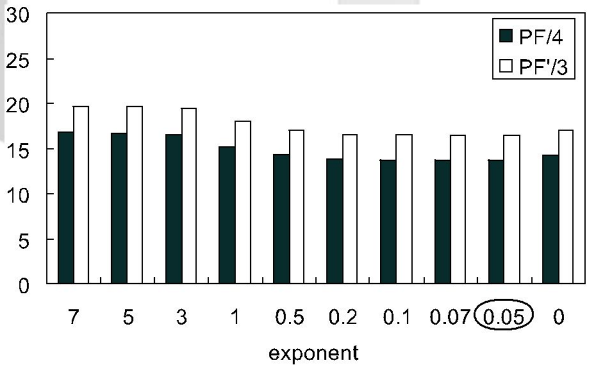


Fig. 6. Performance factors according to exponent change of G equation at low chroma.

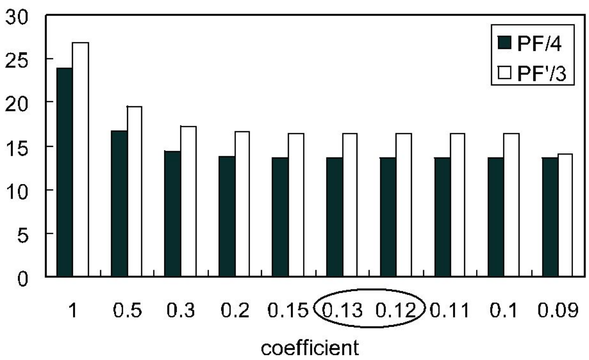


Fig. 7. Performance factors according to coefficient change of G equation at low chroma.

$$\Delta E_{ab}^{*} = \left[(\Delta L^{*})^2 + (\Delta a^{*})^2 + (\Delta b^{*})^2\right]^{1/2}$$

$$L' = L^{*}$$
$$a' = (1+G)a^{*}$$
$$b' = b^{*}$$
$$C' = \sqrt{a'^2 + b'^2}$$
$$h' = \tan^{-1}(b'/a')$$

$$G = 0.12\left(1 - \sqrt{\frac{\overline{C^{*}_{ab}}^{7}}{\overline{C^{*}_{ab}}^{7} + 25^7}}\right)$$

where, $\overline{C^{*}_{ab}}^{7}$: average of sample pair' C^{*}_{ab}

$$\Delta L' = L'_b - L'_s$$
$$\Delta C' = C'_b - C'_s$$
$$\Delta H' = 2\sqrt{C'_b \cdot C'_s}\,\sin\left(\frac{\Delta h'}{2}\right)$$

where, $\Delta h' = h'_b - h'_s$

$$\therefore \Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L \cdot S_L}\right)^2 + \left(\frac{\Delta C'}{K_C \cdot S_C}\right)^2 + \left(\frac{\Delta H'}{K_H \cdot S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C \cdot S_C}\right)\left(\frac{\Delta H'}{K_H \cdot S_H}\right)}$$

$$S_L = 1 + \frac{0.015(\overline{L'} - 50)^2}{\sqrt{20 + (\overline{L'} - 50)^2}}$$
$$S_C = 1 + 0.045\overline{C'}$$
$$S_H = 1 + 0.015\overline{C'} \cdot T$$
$$T = 1 - 0.17\cos(\overline{h'} - 30^\circ) + 0.24\cos(2\overline{h'}) + 0.32\cos(3\overline{h'} + 6^\circ) - 0.2\cos(4\overline{h'} - 63^\circ)$$
$$R_T = -\sin(2\Delta\theta)R_c$$
$$\Delta\theta = 30 \cdot \exp^2\left\{-\left[(\overline{h'} - 275^\circ)/25\right]^2\right\}$$
$$R_c = 2\sqrt{\frac{\overline{C'}^7}{\overline{C'}^7 + 25^7}}$$

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Fig. 8. New a´ for CIEDE 2000 formula for color-difference at low chroma.

Table 4. Comparison of the fit between conventional color-difference formulae and new a´ for data set(l=2)

	CIELAB	CMC	BFD II	CIE94	DCI95	LCD97	LCD99	CIEDE2000	**new a′**
PF/4	14.35	15.98	14.78	14.61	14.66	14.67	15.18	16.73	**13.64**
PF′/3	17.18	18.83	17.62	17.43	17.49	17.49	18.06	19.59	**16.42**
V_{AB}	0.18	0.19	0.18	0.18	0.18	0.18	0.18	0.20	**0.17**
CV	14.82	16.64	15.18	15.15	15.29	15.21	15.75	17.71	**14.02**
g	1.19	1.21	1.20	1.19	1.19	1.19	1.20	1.21	**1.18**
r	0.94	0.93	0.94	0.94	0.94	0.94	0.93	0.92	**0.95**

4. Conclusions

This study was conducted to assist in the deve - lopment of the adjusted color-difference formula that considered color tolerance in the dark region. The conclusions are summarized below.

1. It is found that the CIELAB color difference formula shows the best performance in analysis of low chroma and low lightness color samples.
2. Comparing earlier color-difference studies, it is found that it has a similar level in both the precision of color measurements and the standard error of the observer's judgments.
3. Color tolerance in the dark region confirms the ellipsoid of the long axis, while acceptable color tolerance has a rounder ellipsoid with increasing chroma.

4. The G equation with a chroma factor of CIEDE2000 is used as the base formula. The coefficient of the G equation is revised to 0.12 for adjusting the color-difference in the a*b* plane. A revised CIEDE2000 color difference formula is suggested for the analysis of low chroma and low lightness color samples.

Acknowledgment

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