Chapter 20
Evaluation of the Color-difference Formulae for Neutral Colors

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Abstract In printing industry, the results of quality control of neutral prints are not consistent with the visual assessments. In order to solve this problem, 50 pairs of neutral color samples were prepared, and 29 observers with normal color vision were organized to carry out the color-difference experiments with the method of gray scale. In total, 1750 judgments were gathered. The visual results were used to test the performances of different color-difference formulae in terms of the standardized residual sum of square (STRESS) factor. The results indicate that the CIEDE2000 formulae have the best performance and all the tested formulae have the best performances for the evaluation of the color pairs only with the hue differences.

Keywords Color-difference formulae · Neutral colors · Gray scale · STRESS

20.1 Introduction

It is well known that gray balance is widely used in the processing control, and the quality of printed color samples was usually evaluated by the method of color differences. But many research indicated that the results from the existing uniformity color spaces and color-difference formulae are not well agree with the visual assessments, especially for the neutral colors [1]. CIE Division 1 has investigated the visual differences between two gray color stimuli that may be different in

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Y. Ouyang et al. (eds.), *Advanced Graphic Communications, Packaging Technology and Materials*, Lecture Notes in Electrical Engineering 369,
DOI 10.1007/978-981-10-0072-0_20

chroma and hue, and in obtaining a definition of the percept of gray that is linked to a CIE color metric.

This paper organized 29 observers with normal color vision to carry out the color-difference experiments with 50 pairs of neutral color samples. All the tested formulae predicted that the hue difference near the neutral axis is better than other differences on lightness, chroma, and chroma–hue interaction. The performances of different color-difference formulae were tested, and the formulae were modified by different methods.

20.2 Experimental

20.2.1 Sample Preparation

The color samples were printed on Epson 517 semi-gloss paper by Epson 7908 inkjet printer, and the size of each sample is 4.5 cm × 4.5 cm. The color differences between the samples were ranged from 0.08 to 5.49 CIELAB units with an average color difference of 3.04 CIELAB units. The distribution of the $\Delta E^*_{ab,10}$ values is shown in Fig. 20.1.

A grayscale method as arranged in Fig. 20.2 was used to scale the color differences of sample pairs. The grayscale used in the experiment was prepared to have the same size and material as the samples being used. It was specially

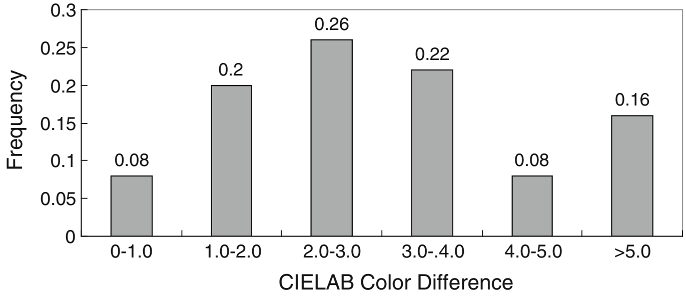

Fig. 20.1 Distribution of CIELAB $\Delta E^*_{ab,10}$ for the 50 pairs studied

Fig. 20.2 The arrangement of samples in the grayscale method

Table 20.1 Colorimetric details of the gray scale prepared under D65/10° condition

Grade	L_s^*	a_s^*	b_s^*	L_c^*	a_c^*	b_c^*	ΔE_{ab}^*	ΔL^*	$\Delta L^*/\Delta E^*$
1	60.06	0.55	−0.55	61.07	0.60	−0.59	1.00	1.00	1.00
2	60.29	0.47	−0.54	62.10	0.15	−0.12	1.88	1.81	0.96
3	59.99	0.36	−0.43	62.96	0.57	−0.61	2.98	2.97	1.00
4	60.14	0.44	−0.50	64.08	−0.26	0.00	4.04	3.95	0.98
5	60.15	0.45	−0.46	65.41	0.06	−0.25	5.27	5.25	1.00
6	59.87	−0.15	−0.21	65.68	0.49	−0.06	5.85	5.81	0.99

designed to have a range from left 1 to right 6 with an interval of approximately 1 unit of $\Delta E_{ab,10}^*$. The CIELAB $L_{ab,10}^*$ attributes for each gray sample and ΔL_{10}^* and $\Delta E_{ab,10}^*$ for each scale are shown in Table 20.1. It can be seen that ΔL_{10}^* and $\Delta E_{ab,10}^*$ values are quite close. This means the quality of grayscale is high.

20.2.2 Visual Assessments

The visual assessments of color difference were conducted in a dark room using a GretagMacbeth Judge II viewing cabinet equipped with a D65 simulator, which had a correlated color temperature of 6441 K and an illuminance value of 900 lx measured by a Photo Research PR-655 Spectroradiometer. The gray background had L_{10}^*, a_{10}^*, and b_{10}^* values of 50.3, 0.2, and 1.3, respectively. The illuminating/viewing geometry was approximately 0°/45° at a viewing distance about 25 cm. The above experimental conditions conform to the standard viewing conditions that CIE recommended [2].

During the experiment, the "sample" pair is given in the bottom of the background (Fig. 20.2), and the 6 "grayscale" pairs are presented in the top of the background. Before the real experiment, observers were trained to assess color difference using the grayscale method. Before each observing session, observers were asked to adapt to the gray background field for about 1 min. The sequence of samples being assessed followed a random order for each observer.

They were instructed to conduct visual assessment using the six grayscale pairs as references. If the color difference of a sample pair was not equal to the color difference of the closest gray scale, observers were encouraged to provide an intermediate value, e.g., 2.6 for a color difference greater than grade 2 but smaller than grade 3.

Figure 20.3 shows the line fitted between the grades of gray scale and their $\Delta E_{ab,10}^*$ values. All visual judgments in grades for each observer were transformed to visual color difference (ΔV) with the equation shown in Fig. 20.3. 29 observers were organized to make the judgments and 6 observers repeated the assessments, so 35 assessments for each sample pair were recorded. In total, 1750 judgments were gathered.

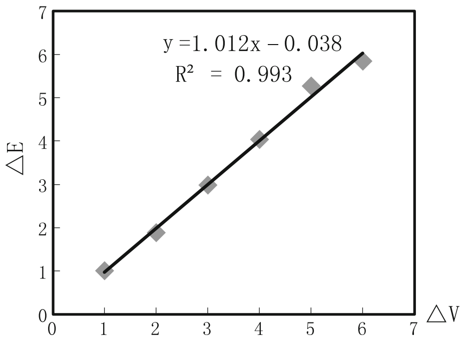

Fig. 20.3 The linear regression between CIELAB color difference and the grade of gray scale

20.3 Results and Discussions

20.3.1 Observers Variation

Observer variations are divided into intra- and inter-observer variability. Observer's intra-variation is used to determine the variation of the visual assessments of a particular observer. Observer's inter-variation represents the average deviation between individuals and the mean visual results for all observers. The intra-variation and inter-variation for this study are calculated by the STRESS unit with $f = 1$. The mean value of the intra-observer variability for the six observers was 33.1 units ranging from 26.4 to 38.2, and the mean value of the inter-observer variability for all observers was 31.9 units ranging from 18.2 to 51.1.

20.3.2 Testing with Color-Difference Formulae

The performances of six color-difference formulae or uniform color spaces, CIELAB, CMC [3], CIE94 [4], CIEDE2000 [5], DIN99d [6], and CAM02-UCS [7], were tested in terms of STRESS [8] using the neutral colors, and two different optimized methods were used to improve the performances of the formulae, the lightness optimization, and the power function method [1]. The results were listed in Table 20.2.

From Table 20.2, the CIEDE2000 formulae have the best performance with the lowest STRESS value. Because CIELAB formulae are not uniform visually for small and medium color difference, in addition, CMC formulae are used for evaluating medium and large color difference in textile industry.

The color-difference formulae modified by power functions provide results in better agreement with visually perceived color differences than the lightness optimization. It is indicated that power functions are useful to improve the performance of current color-difference formulae, as desired by engineers and practitioners in

Table 20.2 Performances of different color-difference formulae in terms of STRESS

	CIELAB	CMC	CIE94	CIEDE2000	DIN99d	CAM02-UCS
Original	23.5	22.8	23.3	*18.3*	20.0	21.9
Optimized (k_L)	23.4 (0.71)	22.7 (0.64)	23.2 (0.77)	*18.1* (0.64)	19.9 (0.6)	21.8 (0.66)
Optimized (power function)	17.7	18.3	18.4	*13.9*	16.1	18.1

Table 20.3 Classification method to paired samples

Subdata	Conditions	Pairs	Mean ΔE^*_{ab}	Max ΔE^*_{ab}
All neutral	$C^*_{ab} \leq 10$	50	3.0	5.5
$\sqrt{\Delta C^2 + \Delta H^2}$	$\sqrt{\Delta C^2 + \Delta H^2}/\Delta E \geq 90\,\%$	46	3.2	5.5
ΔH only	$\lvert\Delta H/\Delta E\rvert \geq 90\ \%$	32	3.3	5.5
$\Delta L + \Delta C + \Delta H$	$\lvert\Delta L/\Delta E\rvert$, $\lvert\Delta C/\Delta E\rvert$ and $\lvert\Delta H/\Delta E\rvert$ are $< 90\ \%$	16	2.9	5.5

Table 20.4 Summary of formula's performance in their original forms

Subdata	CIELAB	CMC	CIE94	CIEDE2000	DIN99d	CAM02-UCS
All neutral	23.5	22.8	23.3	18.3	20.0	21.9
Chromatic only	23.3	22.6	23.0	17.9	19.7	21.4
ΔH only	*21.3*	*21.2*	*21.1*	*17.0*	*19.0*	*20.0*
$\Delta L + \Delta C + \Delta H$	27.6	25.5	27.1	18.5	21.2	25.2

color-quality control and many other color applications, no matter the whole color space or the colors near neutral axis.

The color samples are classified by the method shown in Table 20.3, and the performances of the formulae with their original forms are summarized in Table 20.4 (those italic numbers represent the best performance for each formula).

It is shown in Table 20.4 that the best performance for each formula appeared for the samples with only hue difference in the tested subsets, which is accorded with Cui et al. [9]'s results for the test of neutral colors with $C^*_{ab} \leq 10$ from BFD dataset (see Table 20.5).

Table 20.5 Summary of formulae's performance in Cui's test

Subdata	CIELAB	CMC	CIE94	CIEDE2000	DIN99d	CAM02-UCS
All neutral	30.2	23.7	31.3	25.1	23.6	28.6
Chromatic only	24.2	22.7	23.2	21.2	21.4	24.6
ΔH only	*17.9*	*18.9*	*18.0*	*16.6*	*18.4*	*22.6*
$\Delta L + \Delta C + \Delta H$	31.6	27.7	31.4	27.8	27.5	28.2

20.4 Conclusions

50 pairs of print neutral colors were used to investigate the performance of six color-difference formulae for assessing the colors near neutral axis. The CIEDE2000 formula outperformed others, and the power function method can improve the performance of all the formulae compared with the lightness optimization. Near the neutral axis, all tested formulae performed the best in predicting mainly hue difference, but not well enough for the mixture of different tolerances, especially for mixing with lightness difference.

Acknowledgments This research was supported by National Natural Science Foundation of China (grant 61308081), Beijing Nova Program (NO. Z151100000315076), the Top Young Talents (CIT&TCD201404127), and Young Talents of Beijing Municipal Commission of Education (YETP1465).

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