Evaluation of small suprathreshold color differences under different background colors

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Received October 15, 2013; accepted December 12, 2013; posted online January 23, 2014

A psychophysical experiment under constant stimuli is conducted on a CRT display to measure the visual suprathreshold color differences for five color centers recommended by CIE under the same five background colors. The performances of four CIELAB-based, three CIECAM02-based, and two OSA-UCS-based formulas are tested. Detailed analysis results indicate the existence of chromatic crispening effect. CIEDE2000 performs best for the gray center and gray background, whereas CAM02-LCD and CAM02-UCS have the best performance for non-neutral backgrounds. CAM02-LCD significantly outperforms all other formulas for all color centers under all background colors.

OCIS codes: 330.0330, 330.1720, 330.5510.

doi: 10.3788/COL201412.023301.

The evaluation and optimization of color-difference formulas have been active research fields for decades[1−8]. Parametric effects, as indicated by CIE guideline in 1995[9], might considerably affect the perception of color difference, including illuminant, illuminance level, background, medium, texture, and visual scale. The effect of background color on the perception of color difference has not been considered by any color-difference formula. Specifically, the neutral background is commonly adopted in the evaluation of industrial color-difference. Some published studies[10−12] have indicated that background color could influence the perception of color difference considerably probably because of the crispening effect[13] or the simultaneous contrast effect.

Guan *et al.* investigated the effect of background color on small and large color differences[10,11]. In another study, Xin *et al.* discussed the influence of background color on middle color differences[12]. The results of their studies implied that background colors considerably influenced the perception of color difference, and the existence of the crispening effect was verified. With the rapid development of digital imaging industry, images are usually observed under different chromatic backgrounds. Thus, the influence of background color on the perception of color difference with display colors, e.g., CRT and LCD, should be studied further.

Since the recommendation of CIEDE2000 in 2001 by CIE[4], several color-difference formulas based on other color spaces besides CIELAB have been developed. For example, Luo *et al.* developed three color-difference formulas (CAM02-SCD, CAM02-LCD, and CAM02-UCS) based on the latest color appearance model CIECAM02 in 2006[6]. In the same year, Huertas *et al.* introduced a color-difference formula (OSA-GP) based on OSA-UCS space with small-medium color differences[7]. Oleari *et al.* proposed a Euclidean color-difference formula (OSA-GP-Euclidean) in log-compressed OSA-UCS space in 2009[8].

Most modern color-difference formulas, such as CIE94[3] and CIEDE2000, are developed based on the datasets of small color differences, typically under five CIELAB units[4]. Threshold color difference reflects the perceptibility of human visual system at the level of the just noticeable color difference (JDN). In practical applications, the measurement of color difference, especially the judgment of acceptable color difference, deals with suprathreshold color difference. Small suprathreshold color difference plays an important role in the quality control of color-related industries, such as automobile, printing, dyeing, and digital imaging fields[14].

In this letter, small suprathreshold color differences in the a^*b^* plane of CIELAB space for the five color centers under the same five background colors were evaluated by nine color-difference formulas, including four CIELAB-based formulas (CIELAB, CMC[1], CIE94, and CIEDE2000), three CIECAM02-based formulas (CAM02-SCD, CAM02-LCD, and CAM02-UCS), and two OSA-UCS-based formulas (OSA-GP and OSA-GP-Euclidean). This study aimed to investigate the effects of background colors on small color differences and to evaluate the prediction performances of color-difference formulas for chromatic background colors.

A CRT display of Neso FD570A with 8 bits per channel, which was accurately characterized by using the PLVC model[15] with characterization accuracy of 0.37 CIELAB units, was employed to generate the test color stimuli. The psychophysical method of constant stimuli was adopted. A panel of five observers with normal color vision participated in the visual experiment with a viewing distance of 500 mm. As shown in Fig. 1, two arrays consisting of two $1^\circ\times1^\circ$ squares were placed at the center of the screen as the reference and test pairs, with 0.5° separation between them. Given that a gap exists between two surface samples even when viewed with their edges contacted, a 1-pixel black frame was placed around each square to simulate the viewing condition used in real situation for surface samples. This approach was also employed to diminish the abnormal excessive visual sensitivity possibly caused by the simultaneous effect when two samples are aligned together without the 1-pixel line frame by using display colors, with the background being a $6^\circ\times6^\circ$ square. The left or right position

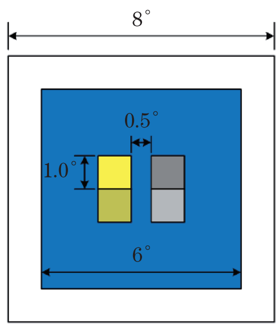

Fig. 1. Arrangement of the test stimulus pattern.

Table 1. CIELAB Values of Color Centers and Background Colors

Color Center and Background Color	L^*	a^*	b^*	C^*_{ab}	h°_{ab}
Gray	62.0	0.0	0.0	0.0	0.0
Red	44.0	37.0	23.0	43.6	31.9
Yellow	87.0	−7.0	47.0	47.5	98.5
Green	56.0	−32.0	0.0	32.0	180.0
Blue	36.0	5.0	−31.0	31.4	279.2

of the reference and test pairs with the upper or lower position for an individual pair was determined randomly by the test software. Outside the background was an 8°×8° white border set as the reference white with lightness of 100 cd/m^2 and chromaticity of CIE D65. The remaining part of the screen was black. All CIELAB values used in this study were calculated under the CIE 1931 standard observer and chromaticity of CIE D65.

Five color centers recommended by CIE in 1978[16] were chosen as the test color centers and background colors. Their corresponding CIELAB values are listed in Table 1. One square of the reference pair was set as the color of the gray center. Another square only had a lightness difference of 3.0 CIELAB units from the former along the positive lightness direction, which was denoted as the visual scale ΔV. For the test pair, one square was set as one of the five color centers, and another square was designed to be evenly distributed every 45° in the a^*b^* plane of CIELAB color space with respect to the former. Along each test direction, the color differences of seven test pairs were predetermined according to a pilot experiment to ensure that the suprathreshold to be measured fell in the range of the color differences adopted by these test pairs. The purpose of this test stimulus pattern was to compare the magnitude of visual color difference of the test pair with that of the reference pair.

Before the experiment, the CRT display was warmed up for at least half an hour to ensure stability. The experiment started with a 2-min dark adaptation, followed by a 1-min background adaptation. Each experiment trial began with a 200-ms black gap procedure. Subsequently, the test stimuli were presented. The experiment ended with a response from the observer. A new assessment was subsequently conducted, and the experiment ended with all test pairs assessed. During the black gap procedure, both reference and test pairs were covered with black, whereas the white border was kept visible to ensure sufficient adaptation to the white point and to eliminate the influence of after image. The visual task of the observers was to determine which pair had larger visual color difference. Every test pair was assessed 10 times by each observer, and all color centers were estimated twice. Thus, the percentages of visual color difference for every test pair larger than that for the reference pair were obtained. To avoid visual fatigue, only one center under one background was assessed by every observer each day. A total of 28,000 trials (5 color centers × 5 background colors × 8 test directions × 7 pairs per direction × 10 assessments per test pair × 2 repetitions per color center) were conducted by each observer; thus, a total of 140,000 visual estimations were performed.

The visual data of suprathreshold color differences in each direction were obtained via the probit analysis algorithm on the basis of maximal likelihood estimation[2] for each observer. These data correspond to the 50% value in the cumulative distribution function[2]. To ensure the accuracy and credibility of the suprathresholds, the intra-observer and inter-observer accuracies were calculated by using STRESS index. This index was introduced by García *et al.* in 2007[17] to compare the discrepancy between two datasets. A larger STRESS index indicates larger discrepancy between two datasets. For a perfect match between two datasets, the STRESS index should be zero. A STRESS index of 30 means that the discrepancy between two datasets is 30%.

The intra-observer accuracy was calculated between the visual results of two repetitions for each observer. The mean accuracy is 17.5 STRESS units, with the largest value of 22.4. The inter-observer accuracy was derived between the suprathresholds for each observer and the average values for all observers, which results in a mean accuracy of 23.8 STRESS units with a maximum of 27.0. Compared with published studies[5,10], the intra-observer and inter-observer accuracies in the current study are between 30 and 40 PF/3 units, which are similar to the STRESS index in magnitude[16]. Therefore, the observer accuracy in this study is considered stable and acceptable.

The suprathreshold chromaticity ellipses in the a^*b^* plane were fitted by using the least-square technique based on the average suprathresholds for all observers along each test direction. The parameters for each ellipse

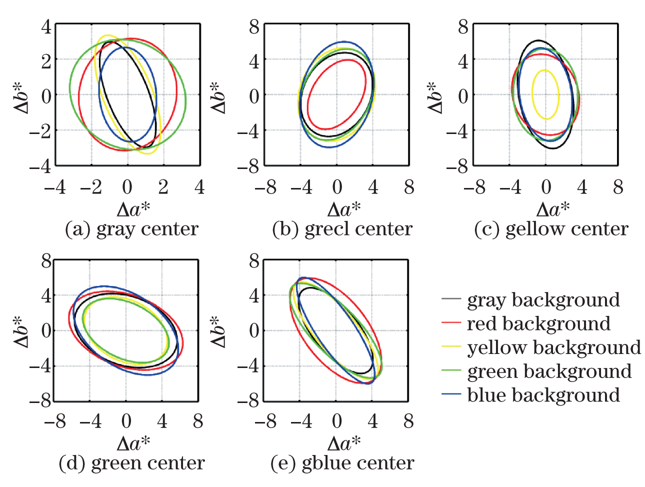

Fig. 2. Chromaticity ellipses for five color centers under different background colors on the average of all observers.

in terms of semi major-axis (A), the ratio of semi-axes (A/B), orientation angle (θ), and the square root of ellipse area ($\sqrt{\pi AB}$) are given in Table 2. The corresponding ellipses for different background colors are illustrated in Figs. 2(a)–(e). The mean fitting accuracy for ellipses is 6.1 STRESS units, indicating that the suprathresholds for each color center could be accurately expressed as an ellipse.

According to Table 2 and Fig. 2, the variances of the orientation angles for the four non-neutral color centers are small with a maximum of 17.8°. For the gray center, the largest discrepancy was found between the red and green backgrounds, with a value of 64.2°. Nearly all ellipses significantly elongate along the semi major-axis except the ones at the gray center under the red and green backgrounds did not elongate, implying the local non-uniformity of the a^*b^* plane.

The ratios of semi-axes (A/B) for all color centers under every background color are illustrated in Fig. 3. According to Table 2 and Fig. 3, the ratios of semi-axes for the red and green centers are nearly constant. For the other three centers, the ratios significantly change with a similar trend in which the ratios become small under the red and green backgrounds. Thus, the visual supra threshold color differences are more uniform under red and green backgrounds than under other backgrounds.

Table 2. Parameters of the Chromaticity Ellipses in the a^*b^* Plane on the Average of All Observers

Color Center	Background	A	A/B	θ	$\sqrt{\pi AB}$
Gray	Gray	3.16	2.75	110.9	3.4
	Red	3.17	1.18	78.3	5.1
	Yellow	3.55	2.59	111.5	3.9
	Green	3.35	1.13	142.5	5.6
	Blue	2.67	1.69	95.6	3.6
Red	Gray	4.94	1.33	63.9	7.6
	Red	4.28	1.57	58.2	6.0
	Yellow	5.39	1.31	69.7	8.4
	Green	5.39	1.43	64.7	8.0
	Blue	6.06	1.53	76.0	8.7
Yellow	Gray	6.15	2.07	99.7	7.6
	Red	4.64	1.28	107.7	7.3
	Yellow	2.77	1.88	93.9	3.6
	Green	5.17	1.44	92.2	7.6
	Blue	5.29	1.84	98.6	6.9
Green	Gray	5.89	1.51	159.8	8.5
	Red	6.57	1.63	159.4	9.1
	Yellow	4.89	1.44	151.4	7.2
	Green	5.10	1.64	153.3	7.1
	Blue	6.49	1.60	144.9	9.1
Blue	Gray	5.83	2.32	128.4	6.8
	Red	6.96	1.98	127.4	8.8
	Yellow	6.84	3.00	129.5	7.0
	Green	6.91	2.66	133.3	7.5
	Blue	7.08	3.40	123.9	6.8

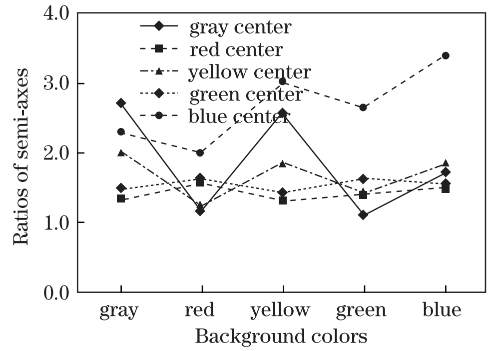

Fig. 3. Ratios of semi-axes for five color centers under different background colors.

Table 3. Variance of Ellipse Shapes for Five Color Centers under Different Background Colors

Color Center	Mean	Min	Max
Gray	22.4	2.3	32.7
Red	4.6	2.1	7.3
Yellow	10.4	4.4	17.4
Green	5.1	2.6	8.5
Blue	9.4	5.8	14.9

To compare the effects of different background colors on the shape of suprathreshold ellipses, 360 points evenly distributed along the contour of each ellipse were chosen, and the distances between these points and the corresponding color center were calculated. For each color center, the ellipse under the gray background was chosen as the reference ellipse. The discrepancies between the reference ellipse and the other ellipses for the same color center were calculated, as listed in Table 3. The mean variance for the gray center under all background colors is the largest (22.4 STRESS units), which is larger than those of the other four centers by at least 12.0 STRESS units. Therefore, different chromatic backgrounds considerably influence the suprathresholds for the gray color center compared with non-neutral color centers.

For comparison, the ellipse areas for five color centers under every background color are plotted in Fig. 4. Considerable discrepancies were found between areas, which imply that the a^*b^* plane is also non-uniform globally for these five color regions. Under all five background colors, the gray center always has the smallest ellipse area. Therefore, the gray center has the highest sensitivity in the a^*b^* plane. The smallest ellipse area for every color center was found under the same background color, implying the existence of chromatic crispening effect. When the chromaticity coordinates of the color stimulus were near to those of the background color, the corresponding visual sensitivity was the highest in comparison with those viewed under other background colors, leading to the smallest measured color tolerance for the same visual color difference.

The prediction performances of the nine color-difference formulas were tested by using the STRESS index, which was calculated between the predicted color differences ΔE and the visual color difference ΔV (3.0 CIELAB units). These color-difference formulas could be divided into three groups, i.e., four CIELAB-based

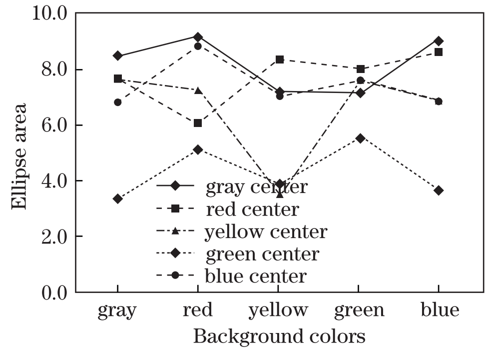

Fig. 4. Ellipse areas for five color centers under different background colors.

formulas (CIELAB, CMC, CIE94, and CIEDE2000), three CIECAM02-based formulas (CAM02-SCD, CAM02-LCD, and CAM02-UCS), and two OSA-UCS-based formulas (OSA-GP and OSA-GP-Euclidean). The predicted color differences were derived between the 360 points evenly distributed along the contour of each ellipse and the corresponding color center by using the original forms of the color-difference formulas, i.e., $k_L = k_C = k_H$=1.0.

The performances of the five color centers under all background colors are presented in Table 4. For each center, the formula with the smallest STRESS value is marked in bold. For the gray center, CIEDE2000 has the best performance because this formula rescaled the a^* axis to make the chromaticity ellipses more circular. This rescaling improved the performance within the neutral region, although the discrepancies among all formulas are smaller than 2.0 STRESS units. CAM02-UCS performs best for the red center, whereas CAM02-LCD outperforms others for the green center. For the yellow center, CMC outperforms CIE94, CAM02-SCD, CAM02-UCS, and CIEDE2000 but by no more than 1.5 STRESS units. For the blue center, OSA-GP-Euclidean has the best performance; nevertheless, the discrepancies between the performances of CIECAM02-based formulas and that of OSA-based formulas are insignificant. CIEDE2000 outperforms all other CIELAB-based formulas by at least 9.6 STRESS units because the orientation angles of the chromaticity ellipses in the blue region were rotated toward the origin of the a^*b^* plane by this formula[4].

Table 5 shows the performances of the color-difference formulas for all color centers under each background color. CIEDE2000 has the best performance of 19.2 STRESS units for the gray background, followed by CAM02-UCS (19.7 STRESS units). Thus, the color-difference prediction efficiency of CIEDE2000 for the gray background was validated, which has also been demonstrated by other studies[4,5]. CAM02-LCD has the best performance for the red and green backgrounds. CAM02-UCS performs best for the yellow and blue backgrounds, which might be attributed to the fact that only CIECAM02 includes the lightness of background during calculation. Although the performance of CIEDE2000 is not the best for the four non-neutral backgrounds, its performance is insignificantly worse than that of the best color-difference formula within 0.6 STRESS units, except in the green background.

Table 4. Performances of Color-difference Formulas for the Five Color Centers under All Background Colors in STRESS

Color Centers	CIELAB	CMC	CIE94	CIEDE2000	CAM02-SCD	CAM02-LCD	CAM02-UCS	OSA-GP	OSA-GP-Eu
Gray	28.6	28.6	28.6	26.6	28.0	27.6	27.8	27.5	27.0
Red	17.3	24.7	23.2	24.8	14.1	14.3	13.2	21.7	19.0
Yellow	29.0	24.1	24.5	25.6	25.0	27.2	25.4	27.3	26.0
Green	19.0	16.7	18.4	18.5	18.2	14.3	16.3	20.6	18.2
Blue	34.2	31.0	30.9	21.3	18.8	17.7	17.8	17.7	17.0

Table 5. Performances of Color-difference Formulas for All Color Centers under Every Background Color in STRESS

Background Colors	CIELAB	CMC	CIE94	CIEDE2000	CAM02-SCD	CAM02-LCD	CAM02-UCS	OSA-GP	OSA-GP-Eu
Gray	33.4	25.3	24.4	19.2	20.4	22.5	19.7	22.7	21.4
Red	26.0	32.3	25.7	26.7	29.8	23.7	26.4	28.3	28.0
Yellow	38.0	40.4	35.9	32.0	33.1	31.5	31.4	35.3	34.7
Green	22.3	36.0	25.0	27.8	27.9	15.3	22.3	27.4	27.2
Blue	35.1	28.0	28.0	22.8	23.5	24.2	22.2	26.0	24.7

Table 6. Performances of Color-difference Formulas for All Color Centers under All Background Colors in STRESS

CIELAB	CMC	CIE94	CIEDE2000	CAM02-SCD	CAM02-LCD	CAM02-UCS	OSA-GP	OSA-GP-Eu
31.8	33.9	28.8	27.3	28.8	25.2	26.2	29.1	28.5

Table 7. Statistically Significant Differences among the Performances of Color-difference Formulas for All Color Centers under All Background Colors by F-test (N=9000, F_C=0.96, $1/F_C$=1.04)

	CIELAB	CMC	CIE94	CIEDE2000	CAM02-SCD	CAM02-LCD	CAM02-UCS	OSA-GP	OSA-GP-Eu
CIELAB		0.88	1.23	1.36	1.22	1.60	1.48	1.19	1.25
CMC	1.14		1.39	1.54	1.39	1.81	1.68	1.36	1.42
CIE94	0.82	0.72		1.11	1.00	1.30	1.21	0.97	1.02
CIEDE2000	0.74	0.65	0.90		0.90	1.18	1.09	0.88	0.92
CAM02-SCD	0.82	0.72	1.00	1.11		1.31	1.21	0.98	1.02
CAM02-LCD	0.63	0.55	0.77	0.85	0.77		0.93	0.75	0.78
CAM02-UCS	0.68	0.59	0.83	0.92	0.82	1.08		0.81	0.84
OSA-GP	0.84	0.74	1.03	1.14	1.02	1.34	1.24		1.05
OSA-GP-Eu	0.80	0.71	0.98	1.09	0.98	1.28	1.19	0.96	

The total performance of color-difference formulas for all color centers under all background colors is shown in Table 6. CAM02-LCD (25.2 STRESS units) outperforms others, followed by CAM02-UCS (26.2 STRESS units) and CIEDE2000 (27.3 STRESS units).

The statistically significant differences among the performances of different color-difference formulas for all color centers under all background colors were calculated via the F-test method[17,18], as shown in Table 7. The formulas in the left column are defined as Formula A and those in the top row are defined as Formula B in the F-test method. N is the number of comparison pairs, and F_C is the lower critical value of two-tailed F distribution with 95% confidence level. According to Table 7, the performance of CAM02-LCD is significantly better than those of the other formulas. CAM02-UCS significantly outperforms other formulas, except CAM02-LCD. CIEDE2000 performs significantly better than the other formulas, except CAM02-LCD and CAM02-UCS.

In conclusion, the suprathreshold color differences for five color centers are measured by the psychophysical method of constant stimuli under the same five background colors by using CRT colors to investigate the influences of different background colors on the perception of suprathreshold color differences. The detailed analysis indicates that background colors considerably influence the ellipsis shape of the gray center compared with that of non-neutral centers. The existence of chromatic crispening effect is validated for all color centers.

The evaluation of nine color-difference formulas demonstrates that CIEDE2000 has the best prediction accuracy for the gray center under all five background colors and all color centers under the gray background color. Meanwhile, CAM02-UCS and CAM02-LCD perform best at all color centers under non-neutral background colors. These two formulas also have outstanding performances for the four non-neutral color centers under all background colors. The prediction of CAM02-LCD for all color centers under all background colors is significantly better than that of all other formulas, followed by CAM02-UCS and CIEDE2000.

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