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A Parametric Colour-difference Study on the Separation Effect

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Abstract

An experiment was carried out to investigate separation and CMF effects on colour-difference evaluation using display colours. In total, 1120 sample pairs around 5 CIE recommended colour centres were assessed 20 times using the grey-scale method. Sample pairs were selected to have colour-difference of 4 and 8 CIELAB units, include or exclude separation between two colours on a pair, have four fields of view (FoVs), 2º, 4º, 10º and 20º. The experiment results were used to test 3 colour-difference equations or uniform colour spaces, CIELAB, CIEDE2000 and CAM16-UCS. For separation (S) sample pairs, CIEDE2000 performed the best, followed by CAM16-UCS and CIELAB the worst. For no-separation (NS) sample pairs, all models gave worse performance than separation (S) sample pairs. The parametric formula derived earlier was verified to predict colour-difference for sample pairs to have no-separation line. Five colour matching functions (CMFs), CIE 1931, CIE 1964, CIE 2006-2º, CIE 2006-10º and 2006-4º were tested and the results indicated very small CMF effect on calculating colour-difference.

Introduction

Colour-difference evaluation has been extensively investigated. A number of colour-difference equations and uniform colour spaces (UCSs) have been developed, e.g., CIELAB [1], CIEDE2000 [2, 3], CAM02-UCS [4], CAM16-UCS [5], etc. Colour-difference should be assessed under a set of reference viewing conditions defined by the CIE [6], i.e., object colours, with a separation or hair-line between two colours on a pair, having colour-difference less than 5 CIELAB (ΔE^*_{ab}) units, homogenous without texture, subtended a viewing angle larger than 4º, illuminated by a D65 simulator at 1000 *lx*, and against a uniform neutral grey background having L^* of 50. But in the pratice applications, the reference viewing conditions are difficult to achieve.

The CIE recommended CIE 1931 2º and 1964 10º standard colorimetric observers or colour matching functions (CMFs) to be used for field of view (FoV) less and larger than 4º, respectively. Taking into account individual's optical densities of lens, macular pigment and visual pigment, CIE 2006 CMF [7] has been proposed for different ages under FoV from 1º to 10º. Note that CIE 2006 CMFs are not intended to replace current CIE 2º and 10º CMFs.

The present study was carried out to investigate separation effect using sample pairs with separation (S) or no-separation (NS) on a display, and CMF effect on calculating colour-difference.

Experimental

Display

The experiment was conducted on a 31-inch NEC PA311D liquid crystal display, with a resolution of 4096 × 2160 pixels. The peak white of the display was set to have a correlated colour temperature (CCT) of 6500 *K* and a luminance of 300 *cd/m*^{2}. The display was characterize using a Gain-Offset-Gamma (GOG) [8] model. The GOG model had a prediction accuracy of 0.35 CIEDE2000 (ΔE_{00}) [2] units over 1120 sample colours in the present experiment, with a standard deviation of 0.20 ΔE_{00} units. In addition, sample pairs were measured 5 times during the whole experimental period, and the mean measured results were used in the analysis. The mean colour-difference from the mean (MCDM) of the 5 measurements was 0.12 ΔE_{00} units, with a standard deviation of 0.05 ΔE_{00} units. The above small values suggest that the display provides high quality, repeatable colours and is suitable for the visual experiments. All the measurements were carried out using a Konica Minolta CS2000A tele-spectroradiometer. The colorimetric values were calculated under D65 and CIE 1964 10º standard colorimetric observer.

Stimuli

The experiment investigated 5 CIE recommended colour centres, grey, red, yellow, green and blue [9]. Table 1 lists the measured CIELAB coordinates of the colour centres under D65 and CIE 1964 10º standard colorimetric observer. Two colour-difference magnitudes, 4 or 8 ΔE^*_{ab} units, were selected. For each colour-difference magnitude, 14 sample pairs were prepared surrounding each colour centre, including 7 pairs with only chromatic difference, 1 pair with only lightness difference, and 6 pairs with mixed lightness and chromatic differences. Sample colours were distributed uniformly from 0º to 180º in $\Delta a^*\Delta b^*$ plane, from 0º to 90º in $\Delta L^*\Delta a^*$ and $\Delta L^*\Delta b^*$ planes. For each sample pair, there were two separation conditions, separation (S) or no-separation (NS) between two colours on a pair. The separation was a one-pixel black line on display. Each sample pair was set to have 4 fields of view (FoVs), 2º, 4º, 10º and 20º. The whole experiment investigated 1120 sample pairs in total (5 centres × 2 magnitudes × 14 samples × 2 (S or NS) × 4 FoVs). Additional, 320 pairs out of them (2 pairs in $\Delta a^*\Delta b^*$ plane, 1 pair in $\Delta L^*\Delta a^*$ plane and 1 pair in $\Delta L^*\Delta b^*$ plane, for each colour centre, magnitude, separation condition and FoV) were repeated to evaluate intra-observer variation and the repetitions were averaged to represent the pairs in the following analysis.

Table 1: CIELAB coordinates of the colour centres under D65 and CIE 1964 10º standard colorimetric observer

	L^*	a^*	b^*
White	61.5	-0.3	-0.3
Red	43.6	37.1	22.5
Yellow	86.3	-6.9	45.3
Green	55.7	-32.1	-0.5
Blue	35.8	5.0	-31.3

Observers

The whole experiment was divided into 4 parts according to the FoVs of 2º, 4º, 10º and 20º. Each stimulus was assessed by 20 observers. In total, 46 normal colour vision observers participated the experiment, including 21 males and 25 females, aging from 19 to 30 years old (with a mean of 24 and a standard deviation of 2.9). Seven observers took part in all parts of the experiment. The others took part in 1 to 3 parts.

Visual Assessment

Figure 1 shows the experimental interface of 4 FoVs. Observers assessed colour-differences of sample pairs using the grey-scale method [10]. The grey-scale pairs were presented on the top of the screen (see Figure 1). The grey-scale samples consisted of 9 ISO 105-A02 samples (GS-1 to GS-5 with an interval of 0.5) [10] and one additional sample (GS-0.5). The grey-scale pairs included two colours, i.e., the standard (GS-5) and each of GS-0.5 to GS-5 samples. The actual grey-scale pairs agreed with ISO standard with a mean difference of 0.1 ΔE^*_{ab} units. Equation 1 was used to transform the grey-scale values (*GS*) to visual-difference values (ΔV). The predicted colour-differences agreed with the actually measured grey-scale pairs with a mean difference of 0.2 ΔE^*_{ab} units.

$$\Delta V = 0.1172GS^4 - 1.7394GS^3 + 9.6987GS^2 - 26.0010GS + 31.8068. \quad (1)$$

The experiment was conducted in a darkened room. Observers seated on a chair and kept their eyes 60 *cm* from the display. Observers adapted the neutral grey background ($L^* = 50$) one minute and then assessed the colour-difference of sample pairs in a random order. Figure 1 shows the arrangement of sample pairs as displayed in the centre of the screen, and grey-scale pairs were shown on the top of the screen. Note that the size of each sample in the grey scale was fixed. This would allow the results from different FoVs to be inter-compared. Observers clicked one of grey-scale pairs to find the similar colour-difference as that of the sample pair. The selected grey-scale pair was displayed on the left or right side of the sample pair. The distance between the edges of the two pairs was fixed at 2.5º for all FoV of the sample pair. Observers reported score in terms of GS with one decimal, e.g., 3.3, using the scroll bar in the bottom of the screen. They can press the 'Previous' or 'Next' button to move to reassess the last pair or move to the next pair. In average, each observer did two sessions, each session to have 180 pairs to complete in 60 minutes.

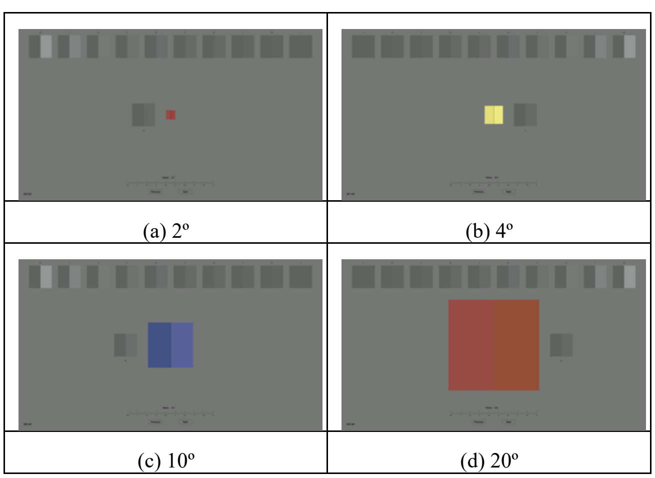

Figure 1. *The experimental interface: (a) 2º, (b) 4º, (c) 10º and (d) 20º.*

Results and Discussions

The standard residual sum of squares (STRESS) [11] metric was used to evaluate the disagreement between the two datasets considered. Equation 2 gives the formula of STRESS:

$$STRESS = 100\sqrt{\frac{\sum(F\Delta E_i - \Delta V_i)^2}{\sum \Delta V_i^2}}, \quad (2)$$

where $F = \frac{\sum \Delta E_i \Delta V_i}{\sum \Delta E_i^2}$, a scaling factor to adjust ΔE and ΔV to the same scale. The STRESS values range from 0 to 100 and smaller values indicate better agreement between the two datasets compared.

Observer Variations

Table 2 lists the inter- and intra-observer variations of each FoV in STRESS units. For inter-observer variation, the STRESS values were 43 (2º), 41 (4º), 42 (10º) and 39 (20º), with an average of 41. Comparing with the S and NS groups, there was very limited difference. Comparing the large and small colour-difference magnitudes groups, the visual difference 8 ΔE^*_{ab} group is consistently smaller than that of 4 ΔE^*_{ab} group. This indicates that observers performed more consistent for assessing larger colour-difference pairs. Comparing 4 FoVs, 2º and 20º had the worst and best consistency, respectively, suggesting the larger viewing fields, the more observer consistency. For the intra-observer variation (320 out of 1120 pairs were repeated), the STRESS values were 27 (2º), 23 (4º), 21 (10º) and 21 (20º), with an average of 23. It can be found observers performed more constantly for larger field size data (10º and 20º).

Table 2: Inter- and intra-observer variations

	2º	4º	10º	20º	Mean
Inter ΔE=4	45	41	45	40	43
Inter ΔE=8	42	40	40	38	40
Inter S pairs	42	41	41	39	41
Inter NS pairs	42	39	41	39	40
Inter Total	43	41	42	39	41
Intra	27	23	21	21	23

Separation Effect

Colour-difference equations and uniform colour spaces were derived using object colours with a separation line between two colours on a pair. So, it is expected that the models to perform better for separation conditions than no-separation conditions. As the standard colour-difference equation widely used across different industries [2], CIEDE2000 performs very well for separation sample pairs. Derived based on the newest standard colour appearance model, CIECAM16 [5], recommended by the CIE, CAM16-UCS had a similar performance to CIEDE2000.

For no-separation (NS) sample pairs, the above models performed much worse than separation (S) sample pairs. Separation (S) and no-separation (NS) pairs had the same predicted colour-differences (ΔE) using a particular colour model, but different visual differences (ΔV). Figure 2 shows the scattering plots of visual difference (ΔV) values from separation (S) and no-separation (NS) pairs. A systematic trend can be found no-separation (NS) sample pairs with and without lightness differences to have larger and smaller visual differences, respectively, compared with separation (S) pairs. This reveals the parametric effect due to separation. When a pair of samples involving some lightness difference with no separation line between two colours on a pair, the visual difference will appear much higher than those with a separation line. Note that all earlier datasets to have sample pairs with a separation line (such as BFD [12, 13], RIT-DuPont [14], Leeds [15] and Witt [16] to develop advanced colour models (BFD, DE94, CIEDE2000, CAM16-UCS, tec.). Until more recently, Mirjalili et al. [17], Zhao et al. [18] and Xu et al. [19] investigated colour-differences using sample pairs having no separation line. Note that in the CIE reference viewing conditions, sample pair should have a separation line.

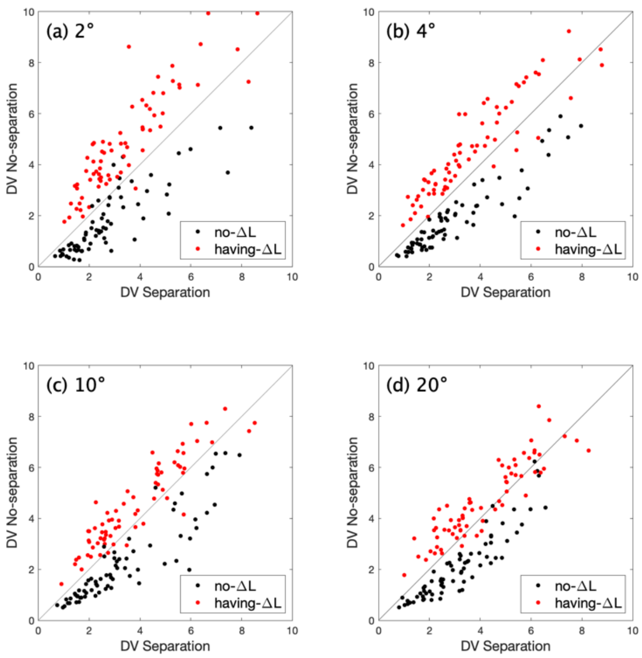

Figure 2. Comparison of visual difference (ΔV) values from separation (S) and no-separation (NS) pairs.

Table 4 lists the STRESS values calculated between ΔV values from the NS and S groups, having pairs of ΔL^*, no-ΔL^* (chromatic) and combined respectively. Comparing the S and NS groups, the pairs having lightness differences had better agreement than those of chromatic differences, and larger FoV subsets had better agreement than smaller sizes. As it can be seen, when combining all the pairs having different FoV differences (see Overall set), the disagreement between the S and NS groups further increased.

Table 4: The STRESS values of ΔV from S and NS groups

S vs NS subsets	No. of pairs	2°	4°	10°	20°	Mean	Overall
ΔL^* set	70	21	19	16	16	18	20
no-ΔL^* set (chromatic)	70	31	21	25	23	25	25
ΔL^* + chromatic	140	36	32	29	26	31	32

Testing Colour Models' Performance

Three colour models, CIELAB [1], CIEDE2000 [2, 3] and CAM16-UCS [5] were tested using the experimental data. Note that only CIE 1964 10° CMF is used in this study, unless it states. Table 3 lists the testing results in STRESS units using separation (S) and no-separation (NS) pairs. It can be found that larger FoV had better performance except 2° and 4° of separation (S) pairs. For separation (S) pairs, CIEDE2000 performed the best, followed by CAM16-UCS and CIELAB the worst. For no-separation (NS) pairs, CAM16-UCS performed better than CIEDE2000 slightly, and CIELAB still the worst. No-separation (NS) pairs had much worse performance than separation (S) pairs.

Table 3: Models' performance in STRESS units

		2°	4°	10°	20°	Mean
S	CIELAB	41	43	38	33	39
	CIEDE2000	20	22	19	17	20
	CAM16-UCS	24	25	22	18	22
NS	CIELAB	51	50	44	44	47
	CIEDE2000	40	37	29	31	34
	CAM16-UCS	39	37	29	30	33

Modelling the parametric effect for NS Sample Pairs

As found by Mirjalili et al. [17], their samples with no-separation had a parametric effect due to the imbedded lightness-difference in total colour-difference. As shown in Figure 2, the NS group sample pairs with lightness difference had larger perceived difference than the S group pairs with lightness difference, but for those chromatic pairs (without lightness difference), the results showed otherwise. Therefore, the typical colour models performed worse for no-separation pairs than separation pairs. Efforts were made to reveal the parametric effect for NS data.

Eq. 3 shows a generic colour-difference formula:

$$\Delta E_0 = \sqrt{(\Delta L)^2 + (\Delta C)^2 + (\Delta H)^2 + RT}, \qquad (3)$$

where RT is the rotation term and is set to zero except for CIEDE2000.

From Figure 2, for no-separation sample pairs having the same colour-difference in CIELAB units, the no-separation pairs having lightness differences should have larger predicted differences than those of chromatic difference. This agrees with the finding from Mirjalili et al. They proposed a colour-difference formula (ΔE_{NS}) given in Eq. 3 by integrating a lightness weighting function (D_L) to predict lightness difference. The lightness difference parametric factor D_L is given in Eq. 4:

$$\Delta E_{\mathrm{NS}} = \sqrt{\left(\frac{\Delta L}{D_L}\right)^2 + (\Delta C)^2 + (\Delta H)^2 + RT}, \qquad (4)$$

where $D_L = a \cdot \Delta E_0 + b$, and the coefficients a and b were obtained from Mirjalili et al.'s dataset, and ΔE_0 was calculated from the original formula Eq. 3. Figure 3 shows Mirjalili et al.'s plot of D_L function against ΔE_0. The function indicates D_L and ΔE_0 values to have a positive correlation, and implies a larger colour-difference, the separation line will show more clearly, would lead to a smaller lightness difference comparing with the chromatic difference.

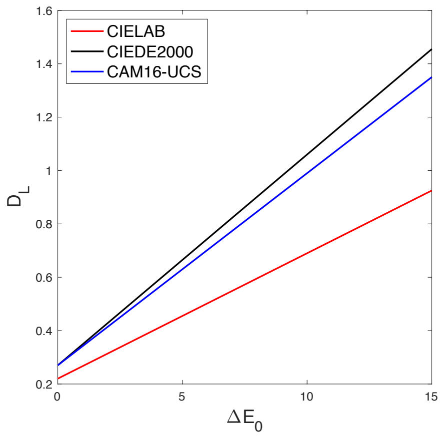

Figure 3. *Factor D_L against the original colour-difference ΔE_0.*

Table 5 lists models' performance in STRESS units to predict NS pairs, before (ΔE_0) and after (ΔE_{NS}) considering separation effect. It can be seen that CIEDE2000 and CAM16-UCS had similar performance and performed better than CIELAB for both ΔE_0 and ΔE_{NS} formulae. Comparing ΔE_0 and ΔE_{NS} according to the F-test, the lightness difference parametric factor D_L gave significant improvement for all models under all FoVs. This indicates there is a separation effect which is modelled well by the D_L function for the data of NS pairs.

Table 5: Models' performance in STRESS units to predict NS pairs, before (ΔE_0) and after (ΔE_{NS}) considering separation effect

	FoV	ΔE_0	ΔE_{NS}
CIELAB	2º	51	35
	4º	50	35
	10º	44	33
	20º	44	30
	mean	47	33
CIEDE2000	FoV	ΔE_0	ΔE_{NS}
	2º	40	30
	4º	37	28
	10º	29	22
	20º	31	21
	mean	34	25
CAM16-UCS	FoV	ΔE_0	ΔE_{NS}
	2º	39	30
	4º	37	28
	10º	29	24
	20º	30	20
	mean	33	26

The Impact of CMF on Colour-difference

In this section, the XYZ values were calculated using the spectral power distribution (SPD) of each sample to multiply one of 5 sets of CMFs, i.e., CIE 1931 2º, CIE 1964 10º, CIE 2006-2º, CIE 2006-10º [20] and 2006-4º [7], to investigate the impact of CMF on colour-difference. The mean age of observers in the present experiment (24 years old) was a parameter to compute 2006-4º CMF based on CIE publication [7]. There are two ways to analyse the data.

Firstly, colour-difference values (ΔE) of the same 3 models, computed using different CMFs were inter-compared with each other using the STRESS metric. Note the visual results (ΔV) were not involved here. The 3 colour models had similar inter-comparison results. Only the results of CAM16-UCS were reported here as an example in Table 6. For 2º observer, CIE 1931 2º and CIE 2006-2º CMFs had a STRESS of 2.6. For 10º observer, CIE 1964 10º and CIE 2006-10º CMFs had a STRESS of 0.7, much smaller than that of 2º observer. This means that the two 10º CMFs agreed better than the two 2º CMFs. Comparing to CIE 2006-4º CMF, the closest was CIE 2006-2º, followed by CIE 1964, CIE 1931, CIE 2006-10º with 1.6, 3.2, 3.3 and 3.5 STRESS units respectively. The largest difference was found between CIE 1931 2º and CIE 2006-10º CMFs (4.4 units). This STRESS value is considered to be extremely small comparing to the inter-observer (41 units) and intra-observer variations (23 units), respectively.

Table 6: Comparison of colour-difference values based on different CMFs in STRESS units

	1964	2006-2º	2006-10º	2006-4º
1931	4.2	2.6	4.4	3.3
1964	--	3.7	0.7	3.2
2006-2º	--	--	4.1	1.6
2006-10º	--	--	--	3.5

The second way is to report the STRESS values between visual differences (ΔV) and colour-differences (ΔE) based on different CMFs to reveal CMF effect. Only the data of separation (S) sample pairs were used here. Again, the 3 models had similar trend and CAM16-UCS was taken as an example. Table 7 lists the testing results. Each row represents the visual differences (ΔV) from each FoV, and each column lists the colour-differences (ΔE) calculated using each CMF. Comparing CMFs under each individual FoV, CIE 1964 10º and CIE 2006-10º had the same and best performance, except for the 10º FoV group. There was no support to use CIE 1931 2º and CIE 1964 10º for sample pairs subtended smaller and larger than 4º respectively. Finally, almost all differences between CMFs were less than 2 STRESS units. This strongly indicates the impact of different CMFs was very small.

Table 7: The performance of CAM16-UCS to predict separation (S) sample pairs in STRESS units (The underlined bold number represents the best performed model.)

	1931	2006-2º	1964	2006-10º	2006-4º
2º	24	25	**24**	**24**	25
4º	26	26	**25**	**25**	27
10º	**21**	22	22	22	22
20º	19	20	**18**	**18**	19

Conclusion

An experiment was conducted using sample pairs to have separation (S) or no-separation (NS) to investigate separation effect. Experiment results from 4 FoVs were compared and larger FoV gave better observer consistency and model performance. CIEDE2000 and CAM16-UCS performed similarly for both S and NS sample pairs, and better than CIELAB. The separation effect was clearly shown, i.e., the lightness difference of no-separation (NS) sample pairs had larger perceived difference than those of the separation (S) sample pairs. A lightness difference parametric function D_L was introduced to derive a new formula ΔE_{NS} for NS pairs. The new formula ΔE_{NS} performed better than the original ΔE_0 significantly.

The impact of different CMFs in calculating colour-differences was also investigated. It was found that the CMF had little effect and the largest difference was found between CIE 1931 and 1964 CMFs, with a STRESS value less than 2 units.

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