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A parametric colour difference equation to evaluate colour difference magnitude effect for gapless printed stimuli

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Abstract

In the present study, attempts were made to investigate the effect of colour difference magnitude on colour difference perception of pairs with no separation. To this end, a large number of printed sample pairs with no separation were prepared around 11 CIE recommended colour centres. The sample pairs, representing four colour difference magnitudes of 1, 2, 4 and 8 CIELAB units, were visually evaluated by a panel of 19 observers using the grey scale method. By comparing the present data set with those previously published using pairs with hair-line separation, it was found that separation had a certain impact on colour difference perception. The visual data were used to test the performance of five colour difference formulae: CIELAB, CIE94, CIEDE2000, CAM02-UCS, and CAM16-UCS. A clear effect of colour difference magnitude on total colour difference perception of pairs with no separation was revealed and a generic simple equation was modelled. By introducing this, a new colour difference equation as the modification of CIEDE2000 was proposed for pairs with no separation. The new formula was found to perform much more precise than the original formulae.

Introduction

Colour difference studies have been active over the last five decades, the aim of which has been to develop a single-number equation representing threshold or suprathreshold perceived colour differences [1]. Such colour difference formulae have been developed based on certain colour discrimination data sets, accumulated under a set of predefined viewing conditions, recommended by CIE [2] for coordinated research on colour difference evaluation.

CIE has specified the D65 simulator at 1000 lux, normal colour vision observers, uniform neutral grey background with L^* of 50, object viewing mode, stimulus size of more than 4° subtended visual angle, nearest possible contact, colour difference magnitude of 0-5 CIELAB units and visually homogeneous sample structure for colour difference evaluations [3]. The psychophysical method for data acquisition is not specified by CIE. However, most of the available datasets have been generated using the grey scale and pair comparison methods. Any deviation from these set of ‘reference’ conditions may affect the perceived colour difference.

In order to minimise the amount of collected data, and to enable results obtained by different researchers to be compared, 19 colour centres have been recommended by CIE [3], from which five colour centres including grey, red, green, blue and yellow are recommended as experimental controls, and the remaining 12 centres provide extended coverage of the colourant gamut.

Following the CIE guidelines for coordinated research on colour difference evaluation [3,4], many efforts have been made to develop colour difference formulae and investigate the effect of various parametric factors on colour difference perception. Current ISO/CIE standard colour difference formula is CIEDE2000, proposed by Luo *et al.* in 2001 [1,5]. In 2006, Luo *et al.* [6] extended the CIE colour appearance model, CIECAM02 [7] to form a uniform colour space named CAM02-UCS. The problem of unexpected computational failure in CIECAM02 has been recently resolved and the new model, CAM16, and its corresponding uniform colour space, CAM16-UCS have been proposed [8].

Such colour difference formulae and colour spaces are developed based on sample pairs with the nearest possible contact, i.e. a hair-line separation. However, in some applications such as printing wallpapers and billboards, colour differences are frequently judged between a pair of samples with no separation in terms of hair-line or a larger gap. In such cases, some problems with respect to ineffectiveness of formula have been reported by the users. However, very little research has been conducted to study the colour difference evaluation of pairs with no separation.

The current CIE standard colour difference formula, CIEDE2000, has been proposed to predict small to medium colour differences within the range of 0-5 CIELAB units. However, the effect of colour difference magnitude on perceived colour differences and validity of predictions by the formula has always been under consideration of CIE [9,10].

In the present study, attempts were made to investigate the effect of colour difference magnitude on perceived colour difference of some printed colour stimuli with no separation in terms of hair-line or larger gaps between the two samples. Eleven colour centres recommended by CIE were chosen to prepare the samples, five of which were the widely investigated grey, red, yellow, green and blue centres. The performance of five colour difference formulae including CIELAB [11], CIE94 [12], CIEDE2000 [1], CAM02-UCS [7] and CAM16-UCS [8] colour difference formulae in predicting the visual data were investigated and finally a new colour difference equation for no separation viewing condition was proposed.

Experiments

Sample preparation

Eleven CIE colour centres distributed uniformly in CIELAB colour space were chosen in this study. These colour centres were grey, red, high chroma orange, yellow, high chroma yellow-green, green, high chroma green, blue-green, blue, high chroma purple, and black. Figure 1 illustrates the distribution of the colour centres in CIE a^*b^* diagram. For each colour centre, a systematic distribution of the samples around the centre in CIELAB colour space was designed and implemented. For each colour centre, samples were distributed around the centre, separately on three perpendicular planes, namely L^*a^*, L^*b^* and a^*b^*. In each plane, the difference between the colour centre and the samples happened only in two directions, while the third variable was kept constant as much as possible. Four levels of colour difference magnitude including 1, 2, 4 and 8 CIELAB units were selected. In this way, 1,012 sample pairs were used in this study.

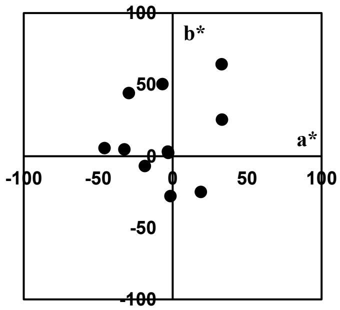

*Figure 1. Distribution of eleven CIE recommended colour centres in CIELAB a*b* plane*

The sample pairs were printed on an HP Latex 365 Printer on an Avery Self-Adhesive Vinyl substrate with CMYKcm inks. The colour centres and their corresponding samples were printed adjacent to each other with no separation between them, constituting an 8×8 cm^2 sample pair. Spectral reflectance of the colour centres and samples was measured using an Xrite SpectroEye spectrophotometer. This portable instrument has a 45˚:0˚ measuring geometry and measures the spectra in the range of 380-730 *nm*.

Psychophysical method

The grey scale method was employed for visual assessment of colour difference. A panel of 19 observers including 10 males and 9 females which were undergraduate and graduate students of the Zhejiang University participated in visual assessment experiments. They were aged between 22 to 33 years old (i.e. average age of 27.5 with standard deviation of 5.5) and all had normal colour vision according to the Ishihara test. The visual assessments were conducted inside a viewing cabinet equipped with spectrum tunable LED lighting system, provided by Thouslite Inc., China, under D65 illumination having the CCT (K), CRI (R_a) and illuminance (lux) of 6460, 97 and 960, respectively. The illumination:observation geometry was always 0°:45°. Figure 2 shows the grey scale samples and a sample pair inside the viewing cabinet. In order to check the observers' accuracy, the grey centre sample pairs were evaluated twice by the observers.

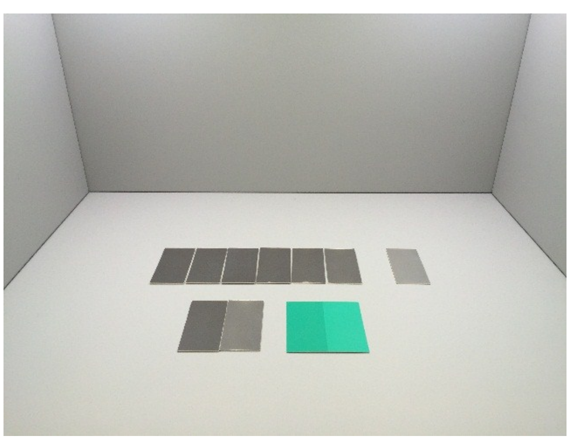

Figure 2. The grey scale samples and a sample pair inside the viewing cabinet

Results and discussion

Observer variability

Grey scale scores reported by the observers were converted to the corresponding visual differences (ΔV). The extent of observers' accuracy in terms of intra-and and inter-observer variability was evaluated using the standardized residual sum of squares (*STRESS*) parameter [13]. The inter-observer variability of 19 observers ranged from 16.4 to 39.2 *STRESS* units with an average of 28.3. This value represents the typical performance of observers in visual assessment of colour difference using the grey scale method [14]. In addition, observers had a better performance in assessing the colour difference of sample pairs in L^*a^* and L^*b^* planes as compared to a^*b^* plane, giving average *STRESS* values of 24.3, 24.7 and 34.0, respectively. The average *STRESS* value of the observations decreased by increasing the colour difference magnitude, indicating a higher observation error involved in assessing the small colour differences. Moreover, the least observation error corresponded to the grey colour centre, having an average *STRESS* value of 21.9. The average intra-observer variability of 19 observers was 16.5 which is less than inter-observer variability.

Effect of colour difference magnitude on visual differences

One way of investigating the effect of parametric factors on colour difference perception is to use the visual differences (ΔV) directly. The visual differences obtained for colour difference magnitudes of 1, 2, 4 and 8 i.e. ΔV-*1*, ΔV-*2*, ΔV-*4* and ΔV-*8*, respectively, were compared in order to investigate the effect of colour difference magnitude on colour difference perception. Figure 3 illustrates the scatter plots of ΔV-*8* against ΔV-*1*, ΔV-*2* and ΔV-*4*. For each plot, the corresponding parametric effect factor, k_E was also calculated using Eq. (1):

$$k_E = \left(\sum_{i=1}^{n} \Delta V_{T,i} / \Delta V_{R,i} \right) / n \tag{1}$$

where $\Delta V_{T,i}$ is the test visual difference and $\Delta V_{R,i}$ is the reference visual difference of stimulus i, and n is the number of stimuli. The k_E factor for ΔV-*8* and ΔV-*1*, ΔV-*8* and ΔV-*2*, and ΔV-*8* and ΔV-*4* visual differences were 5.0, 2.8 and 1.5, respectively, which are reasonably proportional to the corresponding target values of 8, 4 and 2. The largest visual colour difference perceived by the observers was about 5.

Effect of separation on visual differences

The visual results of this work which were produced using the pairs with no separation were summarised as chromaticity discrimination ellipses and compared with Cui *et al.*'s data set [15,16]. Cui *et al.* [15,16] have collected a very comprehensive data set including 16 subsets, varying in stimulus size, background colour, separation and colour of separation, using self-luminous samples on a CRT display. From Cui *et al.*'s data set, four subsets, namely LMG0N in which there was no separation between the samples, together with LMG1G, LMG2G and LMGLG subsets in which there were 1-pixel, 2-pixel and a large 140-pixel grey separations between the samples, respectively, were selected for comparison purposes. Figure 4 illustrates the correlation between the present visual data set, referred to as ZJU data set, and four Cui *et al.* subsets in terms of *STRESS* parameter, for various colour difference magnitudes. Comparing the corresponding *STRESS* values clearly shows that the ZJU data set agrees the best with LGM0N, which was produced using the pairs with no separation.

This strongly suggests that separation has a certain impact on visual colour difference. For pairs with no separation, there is a clear dividing line between the two samples and it affects the colour difference perception. The effect of separation has been discussed in more details in the next section. Moreover, the *STRESS* values decrease by increasing the colour difference magnitude.

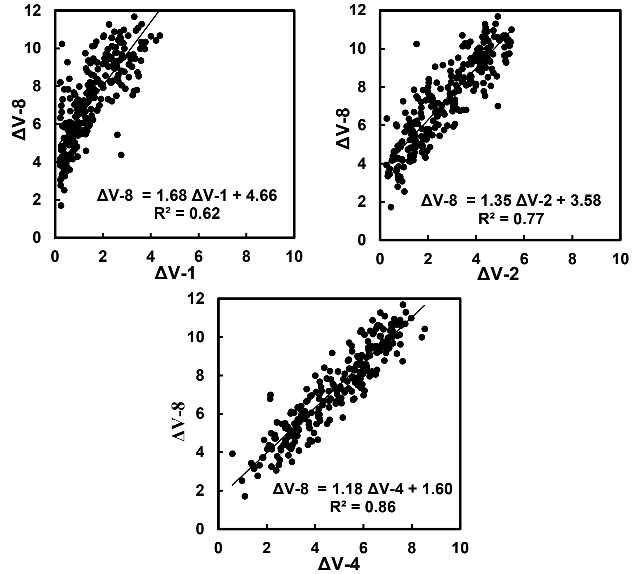

Figure 3. Correlation between various visual differences (ΔV) for different colour difference magnitudes

Performance of colour difference formulae

In a generic colour difference equation, the lightness, chroma and hue parametric factors, k_L, k_C and k_H, respectively, can be adjusted according to different viewing parameters such as textures, backgrounds, separations, etc., for the lightness, chroma and hue, respectively [1]. The performance of a series of colour difference formulae including CIELAB [11], CIE94 [12], CIEDE2000 [1], CAM02-UCS [7] and CAM16-UCS [8] were tested using the present data set. The effect of separation and colour difference magnitude on the performance of colour difference formulae was investigated using three versions of each formula: original, power-corrected, and parametric factor-optimised equations. It is expected that the last two modifications enhance the performances of all formulas.

In the first test, the original form of each colour difference formulae was used in which the lightness and chroma parametric factors k_L and k_C were set to 1. The performance of each formula in predicting the visual differences were then evaluated in terms of *STRESS* parameter. In original form when $k_L=k_C=1$, all formulae markedly outperformed CIELAB. CIE94 performed the best overall followed by CAM16-UCS, CAM02-UCS and CIEDE2000. Figure 5 illustrates the performance of CIEDE2000 colour difference formula for various colour difference magnitudes (ΔE_M) and for the full data set as the combination of all colour difference magnitudes. It is clear that colour difference formula performs better for larger colour difference magnitudes.

The next test was to apply a power factor on formulae. The performance of all formulae improved slightly after power-correction and power factors agreed well across all formulae, ranging from 0.70 to 0.73. Again, CIE94 performed the best.

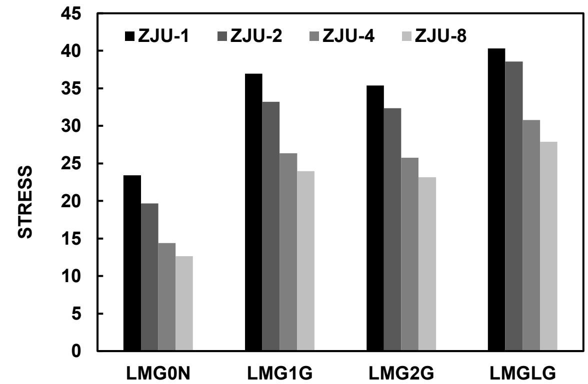

Figure 4. Correlation between the ZJU visual data set and Cui et al. subsets in terms of STRESS

In the last test, modifying the original formulae for parametric factors k_L and k_C also improved the performance of all formulae. However, it was found that chroma parametric factor k_C is always larger than lightness factor k_L indicating that all formulae predicted larger lightness difference than chroma difference with hue difference in between. In addition, for all formulae except CIELAB, the k_C factors were close to 1, ranging from 0.82 to 0.93 while k_L values were always less than 1. This implies that chroma and hue differences are well balanced while lightness difference which is changing across the colour difference magnitude affects the total colour difference. Again, this behaviour can be attributed to the separation effect, i.e. larger perceived colour difference which is mainly lightness difference when there is no hair-line or gap between the samples. In order to test this premise, all formulae were optimised for k_L factor only. However, the performance in terms of *STRESS* did not change considerably. This proves that only k_L factor could be sufficient to describe the effect of colour difference magnitude. The *STRESS* values for power-corrected and k_L-optimised CIEDE2000 formula together with the corresponding optimised k_L values for various colour difference magnitudes are depicted in Figure 5.

Figure 5 shows that k_L values are proportional to the size of colour difference, implying that the contribution of lightness difference to total colour difference reduces when the colour difference increases.

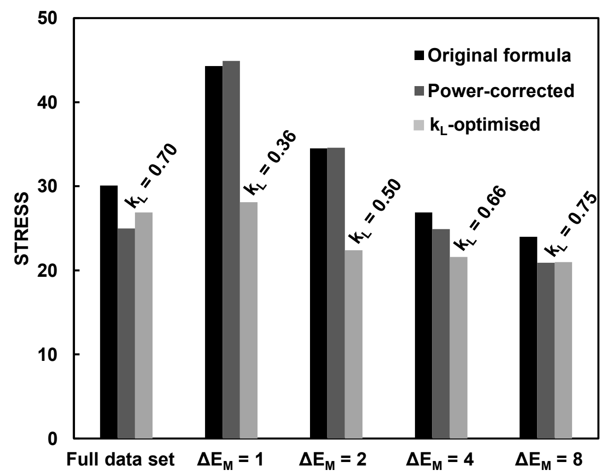

Figure 5. Performance of original, power-corrected and k_L-optimised CIEDE2000 formula in terms of STRESS

Colour difference equation for pairs with no separation

Considering the effect of colour difference magnitude on lightness difference perception of pairs with no separation which was demonstrated in the previous section, a new equation for lightness difference parametric factor (D_L) as a linear function of colour difference (ΔE) was proposed:

$$D_L = a\Delta E + b \tag{2}$$

where a and b are constants to be optimised and ΔE is colour difference. The present data set were used to modify the existing colour difference formulae. For each formula, two modified equations were proposed: magnitude corrected equation (ΔE_1) and power corrected equation (ΔE_2):

$$\Delta E_1 = \sqrt{\left(\frac{\Delta L}{D_L}\right)^2 + (\Delta C)^2 + (\Delta H)^2} \tag{3}$$

$$\Delta E_2 = \left[\sqrt{(\Delta L)^2 + (\Delta C)^2 + (\Delta H)^2}\right]^c \tag{4}$$

For each of the five colour difference formula, a, b and c coefficients were optimised in order to have the highest correlation between the predicted colour differences and the corresponding visual data. The optimised coefficients for the five tested formulae are given in Table 1. The performance of original formulae, and CIEDE2000, together with the modified versions after magnitude correction using ΔE_1 and power correction using ΔE_2 in terms of *STRESS* is also summarised in Figure 6.

Table 1. Optimised coefficients for various colour difference formulae

Colour difference formula	*a*	*b*	*c*
CIELAB	0.05	0.22	0.72
CIEDE2000	0.08	0.27	0.70
CIE94	0.08	0.34	0.73
CAM02-UCS	0.07	0.28	0.72
CAM16-UCS	0.07	0.27	0.73

Comparison between coefficients in Table 1 indicates that these coefficients do not vary much across various colour difference formulae. Although power correction enhanced the performance of all formulae (i.e. ΔE_2), the improvement is not significant. On the other hand, the *STRESS* values corresponding to magnitude-corrected formulae after applying the new equation for lightness difference factor, D_L, drastically decreased, showing the significant improvement in performance of all formulae. Again, the performance of all formulae improves by increasing the colour difference magnitude.

Considering that CIEDE2000 is the current ISO/CIE standard and the most widely used colour difference formula in various industrial applications, it was decided to propose its modified version as the standard formula. It is encouraging that the magnitude-corrected CIEDE2000 gave one of the most accurate predictions of all the colour difference equations. Hence, this equation is designated as the "colour difference formula for 'no separation' viewing condition", ΔE_{NS}, which is given in Eq. (5):

$$\Delta E_{NS} = \sqrt{\left(\frac{\Delta L'}{D_L}\right)^2 + (\Delta C')^2 + (\Delta H')^2 + (\Delta C')(\Delta H')} \tag{5}$$

and $D_L = 0.08\Delta E_{00} + 0.27$

where $\Delta L'$, $\Delta C'$ and $\Delta H'$ are lightness, chroma and hue differences, $(\Delta C')(\Delta H')$ is the interactive term between chroma and hue differences, and ΔE_{00} is the CIEDE2000 colour difference. These terms are calculated according to the same procedure used to calculate the CIEDE2000. ΔE_{NS} is proposed for applications where there is no hair-line or separation gap between the samples under judgment. However, such a trend can also be applied to colour stimuli with hair-line or gap.

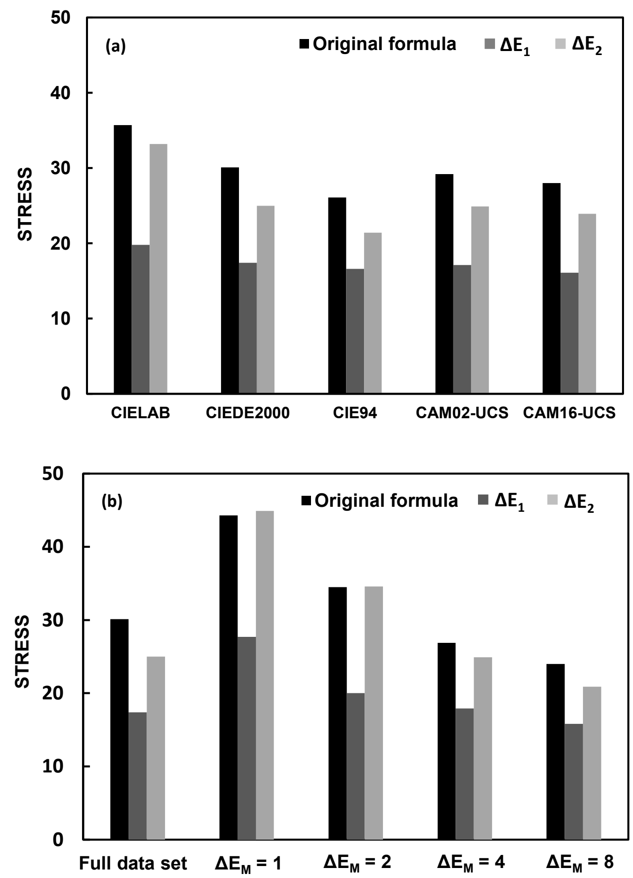

Figure 6. Performance of original, magnitude-corrected and power-corrected (a) colour difference formulae and (b) CIEDE2000 in terms of STRESS

Conclusion

Using a series of printed colour stimuli without separation, the effect of separation and colour difference magnitude on the performance of various colour difference formulae were investigated. The findings are quite interesting which makes provisions for a large improvement in the performance of colour difference formulae by considering the colour difference magnitude effect. The results imply that for pairs with no separation, when colour difference is large, the contrast between the samples is enhanced and it leads to a reduction in the perceived lightness difference and hence the total colour difference. However, this effect was not found for the previously published data sets using hairline pairs. Five colour difference formulae were tested using the visual data obtained using the pairs with no separation and all of them outperformed CIELAB. The effect of colour difference magnitude on perceived colour difference was modelled and the new lightness difference parametric factor function was applied in the five tested colour difference formulae. considering the variation between a large group of observers having inter-observer variability of 28.3 *STRESS* units, CIEDE2000 and CAM16-UCS gave very similar performances, i.e. *STRESS* value of about 17. A new colour difference equation based on CIEDE2000 was developed for pairs with no separation, covering a wide range of colour difference magnitude. The new equation is designated as the colour difference formula for 'no separation' viewing condition: ΔE_{NS}. This equation can be utilized for applications where there is no hair-line or gap between the samples under judgment.

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