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EXTENSION OF COLOUR DIFFERENCE FORMULAE FOR HDR APPLICATIONS

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Abstract

The goal of the work was to extend uniform colour spaces and colour difference formulae for High Dynamic Range (HDR) applications. An experiment was carried out using 140 paint sample pairs to visual assess colour differences of 9 levels from very dark (0.25 cd/m^2) to very bright (1128 cd/m^2) luminance range. The results were used to test and extend 5 colour difference equations to consider HDR application, including CIELAB, CIEDE2000, CAM02-UCS, ICtCp and $J_za_zb_z$.

Keywords: HDR Application, Colour Difference Formulae, uniform colour spaces

1 Introduction

The trend of future imaging devices such as displays, camera will be for the applications of High Dynamic Range (HDR) and Wide Colour Gamut (WCG). Colour difference equation is essential to quantify the image quality. Most of the uniform colour spaces and colour difference formulae are not designed for such applications. For the evaluation of colour reproduction in high dynamic and wide gamut range, the conventional uniform colour spaces and colour-difference equations like CIELAB (CIE, 1995); (CIE, 2001), CIEDE2000 (Luo et al., 2001) and CIECAM02 (Moroney et al., 2002); (CIE, 2004), CAM16 (Li et al., 2017); (Li et al., 2018) cannot be used. The new ones specially derive for HDR/WCG applications such as ICtCp (Dolby，2016) and $J_za_zb_z$ (Safdar et al., 2017) need data to verify their performance. The goals of the research are to provide data to extent the conventional metrics and to test the models' performance in these applications. The research was carried out to study the change of colour difference from very dark to very bright luminance level for judging the colour difference of paint sample pairs. The results were used to extend colour difference equations for HDR application, including CIELAB, CIEDE2000, CAM02-UCS, ICtCp and $J_za_zb_z$. The performance of their original formula and optimised c, γ and K_L formula are reported here.

2 Methods

The experiment was conducted in a viewing cabinet placed in a dark room. The background reflectance was 34%. A spectrum tunable LED viewing cabinet (LEDView) supplied by the Thouslite was used. The light in the cabinet was set to CIE D65 and 1931 standard colorimetric observers. The experiment was divided into nine phases to investigate the colour difference thresholds at different luminance levels from very dark to very bright (0.25, 0.51, 0.90, 1.6, 2.8, 32, 111, 407 and 1128 cd/m^2). Neutral density filters were employed to obtain dark luminance levels lower than 2.8 cd/m^2. One hundred and forty pairs of printed samples were selected from our previous study (Mirialili et al., 2018). They were distributed to surround seven colour centres. Colour pairs in each colour centre included two colour difference magnitudes (2 and 4 CIELAB units). For each magnitude of each centre, there were 2, 3 and 5 pairs in L*b*, L*a* and a*b* planes respectively, as shown in Figure 1. These were printed surrounding seven centres with no hair-line between them. A Konica Minolta CS2000A spectroradiometer was employed to measure the tri-stimulus coordinates XYZ of sample pairs at different luminance levels.

Six categories including '1' for 'no difference', '2' for 'just noticeable difference', '3' for 'small difference', '4' for 'acceptable difference', '5' for 'large difference' and '6' for 'extremely large difference' were employed for visual assessment of colour difference. Twenty normal colour vision observers (ten males and ten females) took part in the experiment. Their ages ranged from 18 to 25 years.

The experiment was divided into nine luminance levels. Each observer attended 3 sessions. Each session took about 1 hour including 3 luminance levels. In total, three hours can finish all the experiment.

These nine luminance levels were arranged in a random order for each observer. Observers sat 60 cm away from the sample pair. The sample pairs had a field of view of 3.5°. The illumination: observation geometry was 0°: 45°. Observers adapted to the viewing conditions for one minute for each luminance level. Subsequently, observers viewed the sample pairs following a random order. The mean category for each pair was calculated to represent the visual data (ΔV). Twenty sample pairs of grey colour centre were repeated in the formal experiment to test the intra-observer variability. In total, 28,800 observations were accumulated, i.e., (140 + 20) pairs × 9 luminance levels × 20 observers, where the 20 pairs were the repeated stimuli for quantifying intra-observer variation later.

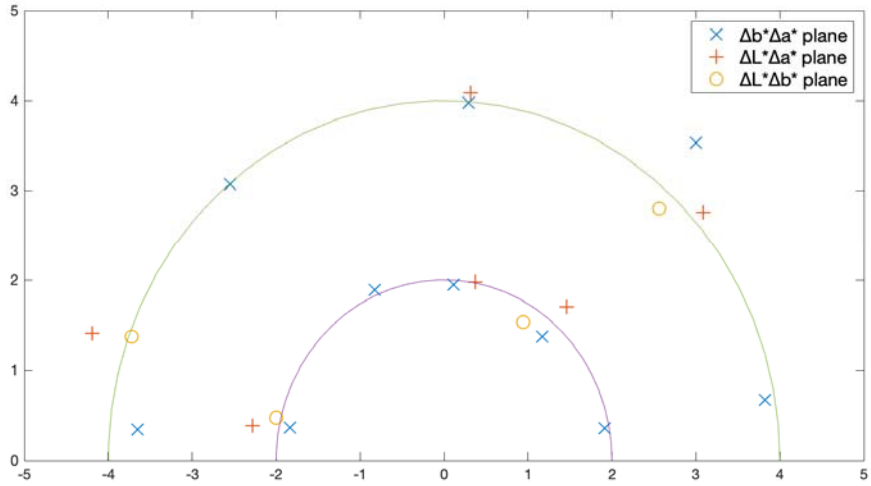

Figure 1 – Colour difference distribution

3 Results

3.1 Inter- and Intra-Observer Variability

The STRESS value (García et al, 2007) calculated from equation (1) was used to indicate the disagreement between two sets of data compared.

$$STRESS = \left(\frac{\sum_{i=1}^{n}(A_i - FB_i)^2}{\sum_{i=1}^{n} F^2 B_i^2}\right)^{1/2} \times 100 \quad (1)$$

with

$$F = \sum_{i=1}^{n} A_i^2 \,/\, \sum_{i=1}^{n} A_i B_i$$

where *n* is the number of sample pairs; *F* is a scaling factor to adjust *A* and *B* data sets on to the same scale.

The percent STRESS values are always between 0 and 100. Values of STRESS near to zero indicate better agreement between two sets of data. In colour-difference studies, a STRESS value exceeding 35 is typically an indicator of the poor performance of the colour-difference formula.

Inter-observer variability was first investigated. The STRESS value was calculated between mean of all the observers and each individual observer's results. The average STRESS value from all observers represent inter-observer variability. It was found the values to be ranged from 15 (at the brightest level) to 25 (at the darkest level) with a mean of 19. Mean intra-observer variability was found to be 24. A clear trend can be found that observers are less consistent for dark luminance levels.

3.2 Colour Difference Thresholds

For obtaining colour-difference thresholds, the visual categorical results from 1 to 6 were rearranged. For each sample pair, the results from the two categories ('1' (no difference) and '2' (just noticeable difference)) were judged as 'not perceptible' pair. The number of these pairs divided by the total number of pairs is called 'not perceivable percentage', or NP%. The NP% of 50% was regarded as perception threshold, which represents half of the observers can perceive the colour difference of the sample pair but the other half cannot. The NP% values were plotted against colour differences calculated from one of the five colour models (CIELAB, CIEDE2000, CAM02-UCS, $J_za_zb_z$ and ICtCp). Probability distribution curves were then fitted to the NP% data. Figure 2 gives an example for CAM02-UCS formula plotted against visual data in NP%. The colour difference threshold (*ΔEt*) was defined to correspond to 50% NP% at each luminance level. The data having NP% below 5% or above 95% were removed from the calculation due to large experimental noise for very large and small colour differences.

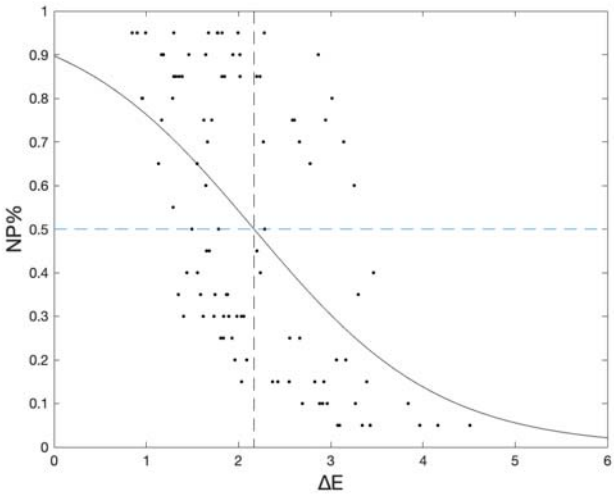

Figure 2 – Probability distribution curves. The abscissa and ordinate are CAM02-UCS ΔE and NP% respectively.

Figure 3 plots *ΔEt* values at all luminance levels. It can be seen that the trends for CIELAB, CIEDE2000 and CAM02-UCS are quite similar, i.e. a decrease of *ΔEt* with an increase of luminance level. However, the trends of ICtCp and $J_za_zb_z$ are opposite, i.e. an increase of *ΔEt* as luminance increases. This could be due to the Picture Quality (PQ) function already imbedded in both models for luminance adaptation. The *ΔEt* values were used to optimize colour difference formulae as HDR correction factors (*c*) in equation (2).

$$c_i = \frac{\Delta Et_1}{\Delta Et_i} \tag{2}$$

where

i ranges from 1 to 9 for each light.

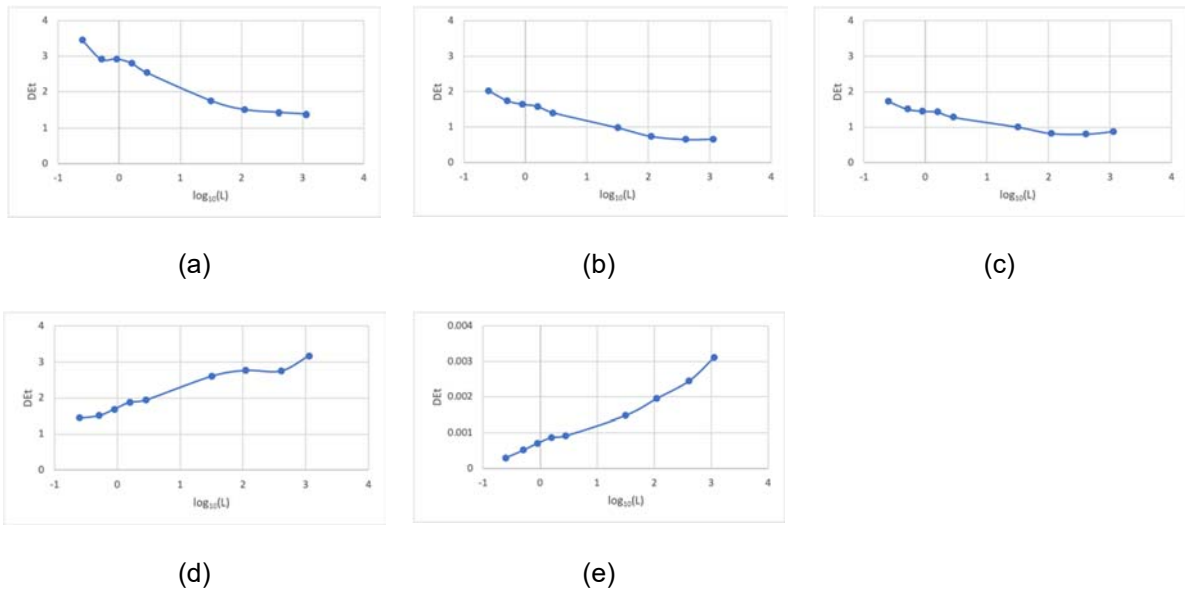

Figure 3 – Colour difference thresholds (*ΔEt*) for a) CIELAB, b) CIEDE2000, c) CAM02-UCS, d) ICtCp, and e) $J_za_zb_z$ respectively.

3.3 Testing the Performance of Colour Models

The STRSS was again calculated between the predicted ΔE values and ΔV values to indicate the five colour models' performance. All luminance levels' data were combined for the surface and luminous model respectively in the calculations. Each colour model had five versions, designated as ΔE_1 to ΔE_5 respectively.

ΔE_1: the original formula.

ΔE_2: the original formula multiplied the ΔE_t coefficient for each luminance level in Figure 3 to consider luminance levels.

ΔE_3: the ΔE_2 formula plus the lightness weighted parameter (K_L) as listed in Table 1.

ΔE_4: the ΔE_2 formula together with the power factor (γ) as listed in Table 1.

ΔE_5: the ΔE_2 formula together with the lightness weighted parameter (K_L) the power factor (γ) as listed in Table 1.

Table 1 –The optimized factors for each space or formula

		ΔE_3	ΔE_4	ΔE_5
CAM02-UCS	K_L *value*	0.66		0.31
	γ *value*		0.45	0.42
ICtCp	K_L *value*	0.91		0.33
	γ *value*		0.40	0.42
CIEDE2000	K_L *value*	0.66		0.22
	γ *value*		0.42	0.39
CIELAB	K_L *value*	0.50		0.15
	γ *value*		0.43	0.40
$J_za_zb_z$	K_L *value*	0.81		0.14
	γ *value*		0.35	0.30

The original colour model is ΔE_1. ΔE_2 is the HDR model which is based on the HDR correction factors derived from the present study. ΔE_3 model is an extension of ΔE_2 by including the lightness parametric factor (K_L). ΔE_4 is the ΔE_3 model with a power factor (γ) as introduced by Huang et al (Huang et al., 2015). ΔE_5 is a full model to include all the 3 corrections, c, K_L and γ. Table 1 results showed that for ΔE_3 formula, all K_L values are less than one, indicating a more significant lightness difference than the chroma and hue differences, and for ΔE_4 formula, the γ factors for all formulae are quite similar, ranged from 0.35 to 0.45. As for ΔE_5 formula, the lightness parametric factor of each formula was much smaller than that in ΔE_3 and similar γ factor as in ΔE_4.

Table 2 – Models' performance expressed in STRESS unit

	STRESS				
	CAM02-UCS	ICtCp	CIEDE2000	CIELAB	$J_za_zb_z$
ΔE_1	35	47	44	44	67
ΔE_2	39	36	42	42	47
ΔE_3	36	36	39	35	47
ΔE_4	25	24	29	32	29
ΔE_5	18	18	19	19	21

Table 2 summarizes the performance of the five versions of each space or formula. Comparing the five versions for each space or formula, it can be clearly seen some improvement from ΔE_1 to ΔE_2 caused by the HDR scaling factors except for CAM02-UCS. Large improvements can be found in ΔE_3 and ΔE_4 due to the introduction of the K_L and γ factors, respectively. Finally, ΔE_5 always gave the best performance to include all 3 parameters. As comparing different formulae, CAM02-UCS and ICtCp performed the best, followed by CIEDE2000 and CIELAB, and $J_za_zb_z$ performed slightly worse.

4 Conclusions

A psychophysical experiment was carried out to estimate 140 colour differences from very dark to very bright luminance range including 9 levels. The results were used to establish JND tolerance at different luminance levels. It can be used to extend uniform colour spaces and colour difference equations for high dynamic range application. In addition, the optimized lightness parametric factor, power factor and combination of them were added to improve 5 spaces and formulae: CIELAB, CIEDE2000, CAM02-UCS, $J_za_zb_z$ and ICtCp. CAM02-UCS and ICtCp performed the best, followed by CIEDE2000 and CIELAB, and $J_za_zb_z$ performed slightly worse.

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