Colour difference evaluation under illuminant A

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ABSTRACT

Various colour difference formulae and uniform colour spaces based upon colour appearance model CIECAM02 were tested using a data set collected under illuminant A. It was found that all formulae or spaces developed from the data under daylight source cannot accurately predict the colour differences under illuminant A. It suggests that for evaluating the colour differences under non-daylight source, it is better either to apply a colour appearance model, or to transform the non-daylight data to daylight using a chromatic adaptation transform and then to calculate the colour differences as usual.

1. INTRODUCTION

Many colour-difference formulae, such as CMC[1], CIE94[2], BFD[3], LCD[4], and CIEDE2000[5], were developed by modifying CIELAB[6] since 1976, but none of these has an associated uniform colour space (UCS). In 2002, Cui *et al* derived a colour space DIN99d[7] based on the DIN99[8] colour space. It was adopted as a German standard. DIN99d gives very close performance as CIEDE2000, the present CIE recommended colour difference formula, but has an associated colour space and much more uniform than CIELAB space. More recently, some uniform colour spaces based upon the CIECAM02[9] colour appearance model were developed for evaluating colour differences[10].

Colour differences assessment is typically assessed under daylight in industrial practice. So that most of the data collected for developing colour difference formulae were generated under daylight simulator. However, the commercial products such as garment purchased by customers are always being assessed under a non-daylight source such as tungsten, cool white fluorescent lamps. Hence, the perceived colour differences under light sources other than daylight are important for assessing metamerism. A pair of samples may be an acceptable match under daylight but quite unacceptable under non-daylight such as CIE illuminant A, and F11. For calculating the colour differences of a pair of samples under a different illuminant, we usually use the corresponding reference white of the illuminant. The question arose here is whether a colour difference formula developed from data gathered under a daylight source can be successfully applied for those under non-daylight sources.

2. MEASURE OF FIT

In this study, the PF/3[11] value, which is a combination of three statistical measures, γ[12], CV[12] and V_{AB}[13], was again used to indicate the performance of a colour difference formula. In addition, F test was used to reveal the significance difference between two different formulae.

F test was first proposed by Alman[14] in 2000 for testing the statistical significance between CIEDE2000 and its reduced models in predicting a particular data set. The testing hypothesis is described below, for which V_M was calculated differently as that original proposed[14] by removing the intercept in the equation.

(1) Formulate the null and alternate hypotheses (two-tailed)
H_0: $V_A = V_B$ (*e.g.* two formulae without significance difference)
H_A: $V_A \neq V_B$ (*e.g.* two formulae with significance difference)

(2) Calculate the F value: $F = V_A / V_B$ where

$$V_M = \sum_{i=1}^{N} \left(\Delta V_i - a_M \Delta E_{Mi}\right)^2 /(N-1) \qquad M \in \{A, B\}$$

(3) Reject the hypothesis (H_0) if $F > F_C$ or if $F < 1/F_C$

where $F_C = F(df_A, df_B, 0.95)$ is the critical value of F distribution with 95% confidence level and df_A and df_B degrees of freedom, F_C can be found from statistical textbooks; V_A and V_B represent the residual error variances after scaling correction for Formula A and B, respectively. The $a_M = \Sigma(\Delta E_{Mi}\Delta V_i)/\Sigma(\Delta E_{Mi})^2$ are the slope between the visual results ΔV and the ΔE from Formula A and B, respectively. Finally, N is the number of samples in the data set, and $df_A = df_B =$ N-1 in this study.

3. TESTING COLOUR DIFFERENCE FORMULAE UNDER ILLUMINANT A

The available colour discrimination data[15] under illuminant A, all based on perceptibility studies involving small colour differences between surface colours, was collected at the University of Bradford. In total, there are 1053 pairs of samples around 51 colour centres with an average ΔE^*_{ab} of 2.9. This data is called BFA in this study.

The BFA data was first used to test the performance of CIELAB and its seven modified versions: CMC, CIE94, CIEDE2000, BFD, LCD, DIN99d and BFDA[15]. The BFDA formula was developed to fit the above data by Luo *et al* and is the only one formula available for calculating the colour differences under illuminant A. The testing results are summarised in Table 1. It showed that after applying suitable parametric factors (k_L) respectively, all formulae except CIELAB and BFDA in Table 1 gave very similar performance, i.e. with PF/3 values ranged from 34 to 37, and all performed worse than that of the best formula BFDA but much better than CIELAB. This indicates that the formulae developed under daylight sources cannot accurately predict the colour differences under non-daylight sources such as illuminant A.

Table 1: The performance of colour difference formulae under illuminant A

	CIELAB	CMC	CIE94	CIEDE2000	BFD	LCD	DIN99d	BFDA
PF/3	53	37	42	37	35	39	36	**25**
k_L	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PF/3	52	37	35	35	35	36	34	**25**
Optimised k_L	0.84	1.21	1.74	1.37	0.95	1.47	1.39	1.00

The difference of a pair of above colour difference formulae in predicting colour differences under illuminant A was also evaluated using F test. The results are listed in Table 2 and marked with bold and italic if the difference is statistically significant. The upper and lower critical values to accept the hypothesis H_0 are 1.129 and 0.886 of the 95% confidence level, respectively. The F value within this range implies the difference between the two models tested is insignificant. The results in Table 2 showed that CIELAB, BFDA, and CMC (in most cases) were significantly different from the other formulae, but CIELAB and CMC performed significantly worse than the others (with F value > 1 in each row for which CIELAB or CMC is the numerator in F ratio). This indicates the residual error variance from CIELAB or CMC is larger than that from other formulae. Conversely, BFDA performed significantly better than the others (with F value > 1 in the last column for which BFDA is the denominator in F ratio).

Table 2: The significance test of two colour difference formulae under illuminant A

Model A \ Model B	CIELAB	CMC	CIE94	CIEDE2000	BFD	LCD	DIN99d	BFDA
CIELAB		***1.921***	***2.126***	***2.264***	***2.170***	***2.063***	***2.267***	***3.875***
CMC	***0.521***		1.107	***1.179***	***1.130***	1.074	***1.180***	***2.017***
CIE94	***0.470***	0.903		1.065	1.021	0.970	1.066	***1.822***
CIEDE2000	***0.442***	***0.848***	0.939		0.959	0.911	1.001	***1.712***
BFD	***0.461***	***0.885***	0.979	1.043		0.951	1.045	***1.785***
LCD	***0.485***	0.931	1.031	1.098	1.052		1.099	***1.878***
DIN99d	***0.441***	***0.847***	0.938	0.999	0.957	0.910		***1.709***
BFDA	***0.258***	***0.496***	***0.549***	***0.584***	***0.560***	***0.532***	***0.585***	

Note: each model is embedded an optimised k_L parametric factor

In the next analysis, the BFA data was first transformed to illuminant D65 using a chromatic adaptation transform model, CAT02[9], which was included in the new CIE colour appearance model

CIECAM02, and then used to test the colour difference formulae. The performances of new method are summarised in Table 3. Comparing the results from Table 3 with that from Table 1, it can be seen that the performance of all the formulae has a reasonable improvement (PF/3 reduced by at least 2 units consistently for all formulae) after transforming the BFA data from illuminant A to illuminant D65. This further verifies that colour difference formulae developed under one illuminant such as D65 cannot accurately predict data under other illuminants, e.g. illuminant A.

Table 3: The performance of CAT02 plus colour difference formulae

	CIELAB	CMC	CIE94	CIEDE2000	BFD	LCD	DIN99d
PF/3	50	35	39	33	**31**	36	32
k_L	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PF/3	49	34	33	31	31	33	**29**
Optimised k_L	0.87	1.23	1.74	1.37	0.97	1.49	1.40
F Test	***1.137***	***1.188***	***1.200***	***1.256***	***1.303***	***1.205***	***1.341***

For revealing the difference between the original formulae and the new method in predicting colour differences under illuminant A, F test was applied again (with the original formulae as the numerator in the F ratio), the results are listed in the last row of Table 3 and marked with bold and italic if the difference is significant. It demonstrated from Table 3, the F values from all formulae are larger than 1, this clearly indicates that the original formulae are worse than the new method in predicting colour differences under illuminant A, and particularly, all the F values fell outside the range from 0.886 to 1.129, this exposes that the difference between two tested models is statistically significant to the 95% confidence level.

Finally, the colour appearance model CIECAM02 and its four extensions[10] SCDUCS, SCDUCS', LCDUCS, and LCDUCS' were tested using the current data BFA and the results are summarised in Table 4. The above four CIECAM02 extensions were developed based on CIECAM02 by Li *et al* [10] for evaluating colour differences, any one of them acts as a combination of a chromatic adaptation transform model and a colour difference formula. The prefix SCD and LCD indicate the model was developed to fit small and large colour difference data sets, respectively. Comparing the results from Table 4 with Table 3, it disclosed that colour spaces SCDUCS' and SCDUCS based upon small colour differences performed similarly to the combinations of CAT02 and advanced colour difference formulae such as CMC, CIE94, CIEDE2000, BFD, LCD and DIN99d.

Table 4: The performance of CIECAM02 and its extensions for evaluation of colour differences

	CIECAM02	SCDUCS	SCDUCS'	LCDUCS	LCDUCS'
PF/3	43	38	**34**	44	40
k_L	1.00	1.00	1.00	1.00	1.00
PF/3	43	34	**32**	39	37
Optimised k_L	1.02	1.56	1.37	1.61	1.41

Table 5: The difference between different formulae in predicting colour difference under illuminant A

Model A \ Model B	CIECAM02	SCDUCS	SCDUCS'	LCDUCS	LCDUCS'
CIELAB	***1.381***	***2.304***	***2.550***	***1.679***	***1.798***
CMC	***0.719***	***1.200***	***1.327***	0.874	0.936
CIE94	***0.650***	1.084	***1.199***	***0.790***	***0.846***
CIEDE2000	***0.610***	1.018	1.126	***0.742***	***0.794***
BFD	***0.636***	1.062	***1.175***	***0.774***	***0.829***
LCD	***0.670***	1.117	***1.236***	***0.814***	***0.872***
DIN99d	***0.609***	1.016	1.125	***0.741***	***0.793***
BFDA	***0.356***	***0.595***	***0.658***	***0.433***	***0.464***
CIECAM02		***1.668***	***1.846***	***1.216***	***1.302***
SCDUCS	***0.600***		1.106	***0.729***	***0.780***
SCDUCS'	***0.542***	0.904		***0.659***	***0.705***
LCDUCS	***0.822***	***1.372***	***1.517***		1.071
LCDUCS'	***0.768***	***1.282***	***1.418***	0.934	

Note: each model is embedded an optimised k_L parametric factor

The differences between the formulae based upon CIECAM02 and those based on CIELAB were also tested using F test. The results are listed in Table 5. It clearly shows that the advanced formulae based upon CIELAB excluding CIELAB itself are significantly better than CIECAM02, LCDUCS, and LCDUCS', and all the four CIECAM02 extensions are significantly better than CIECAM02 in predicting colour differences under illuminant A. The models SCDUCS and SCDUCS' developed from small colour differences data, especially SCDUCS', are significantly better than the most formulae based upon CIELAB (which F value larger than 1 in the column SCDUCS') except for BFDA.

4. CONCLUSIONS

The colour difference formulae developed based on the data under one illuminant, such as D65, cannot accurately predict the data from the other illuminants, such as A. There are two possible ways to calculate the colour difference of a given pair of samples under a non-daylight source; one is to first transform the data from non-daylight to daylight using a chromatic adaptation transform and then to calculate the colour difference under a daylight source. Another method is to use a colour space developed based up a colour appearance model.

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