Combining Colour Appearance Model with Colour Difference Formula

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ABSTRACT

There are many advantages to apply a single universal colour model to perform all colorimetric applications. One promising approach to achieve this is to extend colour appearance models for evaluating colour differences. Colour appearance models have been developed to predict the colour appearance under different viewing conditions. They are also capable of evaluating colour differences because of the inclusion of a uniform colour space. This paper describes the performance of the CIE 2002 colour appearance model, CIECAM02, in predicting three types of colour discrimination data sets: large and small magnitude colour-differences under daylight illuminants, and small magnitude colour differences under illuminant A. The results showed that CIECAM02 gave performance similar to the best available formulae and spaces. The CIECAM02 was further extended to give the most accurate performance in predicting all types of colour discrimination data sets.

1. INTRODUCTION

Colorimetry has been widely used in three main application areas: colour specification, colour difference evaluation and colour appearance prediction. The research has been conventionally conducted separately in each area. Over the years, separate colorimetric models have been developed to fit colour appearance and colour difference data. However, Luo *et al*[1] demonstrated that their colour appearance model, LLAB, gave reasonable predictions to both types of data sets. This implies some similarity between the colour difference and colour appearance data. In 1997, CIE recommended an interim colour appearance model, CIECAM97s[2] in predicting corresponding colour appearance to achieve cross-media colour image reproduction. In 2002, CIECAM02[3] was adopted by CIE which is a revision of CIECAM97s for improving its accuracy performance and simplifying the structure of model. *Li et al*[4] then tested both colour appearance models using two distinct types of colour difference data sets as found by Zhu *et al*[5] : large and small colour differences, designated as LCD and SCD types, respectively. *Li et al* revealed that the best structure for predicting colour difference for both colour appearance models is a polar space consisted of lightness, colourfulness and hue angle. (Note that these models include many colour scales: lightness, brightness, colourfulness, chroma, saturation, hue angle and hue composition.) They also found that CIECAM02 outperformed CIECAM97s in all structures of spaces. Its performance is close to some of the best available colour difference formulae or uniform colour spaces. This indicates that CIECAM02 could be a good candidate to be a universal colour model for all colorimetric applications. The term, 'uniform colour space', used here is defined by the CIE[6] as a three-dimensional colour space in which equal distances approximately represent equal colour differences.

This paper describes two uniform colour spaces based upon CIECAM02, which were simply modified versions to fit the LCD and SCD data sets. In addition, the new spaces were also tested using a colour difference data set under illuminant A. Currently, there is no CIE recommendation to calculate colour differences under non-daylight illuminants.

2. EXPERIMENTAL DATA SETS

Many colour difference data sets are gain used in this study. The LCD group[5] includes six data sets: CII-Zhu, OSA, Guan, BADB-Textile, Pointer and Munsell. They have 144, 128, 292, 238, 1038 and 844 pairs respectively and CIELAB[7] colour-difference values ranged from 9 to 14 with an average of 10. These data sets were based on not only surface materials including textile, paint, ink but also CRT colours.

The SCD data used in this study is a combined data set[8] including four data sets: BFD, RIT-DuPont, Leeds and Witt. This combined data was used to derive the most recent CIE recommended colour difference formula, CIEDE2000[8], and DIN99d[9] colour space. It includes 3652 sample pairs with an average of 2.5 CIELAB ΔE units.

Another data set[10] accumulated at the University of Bradford under illuminant A was also used to test the performance of formulae and spaces for non-daylight illuminants.

3. NEW CIECAM02 BASED UNIFORM COLOUR SPACES

3.1 Modification of CIECAM02

Following the same strategy as our earlier work[4,5], various colour difference formulae and uniform colour spaces based upon the lightness *(J)*, colourfulness *(M)* and hue angle *(h)* of CIECAM02 were developed. The aim of this study was to derive a model having a simple structure with the least modification to the original CIECAM02. The strategy was to determine a generic model including some coefficients to fit different data sets in a particular data type. The PF/3 measure of fit[11], which is a combination of three statistical measures (gamma, CV and V_{AB}) was again used. An optimisation technique were used to obtain the model coefficients by minimising the PF/3 value. A zero PF/3 value means a perfect agreement and a value of 30 indicates a 30% disagreement between the model's predictions and visual results.

Finally, two spaces, named CAM02-LCD and CAM02-SCD, were selected given in eqs.(1) and (2) respectively. They were fitted to the LCD and SCD data sets respectively.

$$\Delta E_{CAM02-LCD} = \sqrt{(\Delta J'/K_L)^2 + \Delta a_{LCD}{}^2 + \Delta b_{LCD}{}^2} \qquad (1)$$

where

$$J' = \frac{1.7J}{1+0.007J}$$

$$M_{LCD} = (1/0.0053)\ln(1+0.0053M)$$

$$a_{LCD} = M_{LCD}\cos(h), \qquad b_{LCD} = M_{LCD}\sin(h)$$

$$\Delta E_{CAM02-SCD} = \sqrt{(\Delta J'/K_L)^2 + \Delta a_{SCD}{}^2 + \Delta b_{SCD}{}^2} \qquad (2)$$

where

$$J' = \frac{1.7J}{1+0.007J}$$

$$M_{SCD} = (1/0.0363)\ln(1+0.0363M)$$

$$a_{SCD} = M_{SCD}\cos(h), \qquad b_{SCD} = M_{SCD}\sin(h)$$

where *J, M, h* are the CIECAM02 lightness, colourfulness and hue angle, respectively. The $\Delta J'$. Δa and Δb are the *J', a* and *b* differences between the 'standard' and 'sample' in a pair. The K_L values are 0.77 and 1.24 for CAM02-LCD and CAM02-SCD models, respectively.

The performance of the CIECAM02, CAM02-LCD and CAM02-SCD together with the best available colour difference formulae or uniform colour spaces are summarised in Table 1, in which each formula was optimised with a K_L parameter. Also, the formulae and spaces are listed according to their PF/3 values in fitting LCD, SCD (daylight illuminants) and SCD (illuminant A) data sets. The PF/3 value for each formula or space was calculated using the arithmetic mean of all the data sets in each data group. This means that equal weight was applied to each individual data set.

Comparing different uniform colour spaces' performance using the LCD data sets in Table 1, the results showed that CAM02-LCD outperformed the other models. This implies that simple modifications gave obvious improvement from the worst CIECAM02 to the best CAM02-LCD. However, all models gave similar performance within a 5 PF/3 value. Also, CIECAM02 performed similarly to other spaces derived solely from the LCD data sets. This implies that there is a great similarity between the colour appearance and LCD data sets.

Table 1: Testing uniform colour spaces and colour difference formulae using the LCD, SCD and SCD illuminant A data sets

Tested Using the LCD data sets	PF/3	Tested Using the Combined Daylight SCD data set	PF/3	Tested Using the Illuminant A SCD data set	PF/3
CIECAM02	27	CIELAB	52	CIELAB	52
CIELAB	26	CIECAM02	47	CIECAM02	43
IPT[12]	26	CMC[15]	38	CMC	37
Kuehni[13]	25	CIE94[16]	37	CIEDE2000	35
OSA	25	DIN99d	35	DIN99d	34
GLAB[14]	24	**CAM02-SCD**	**34**	**CAM02-SCD**	**32**
CAM02-LCD	22	CIEDE2000	33	BFDA[10]	25

Note: each model is embedded an optimised K_L parametric factor.

Comparing different models' performance using the combined SCD data in Table 1, the results showed that CIEDE2000 and BFD outperformed the other models with CAM02-SCD the second best, only one PF/3 unit worse than the best ones. As expected, the worst performed ones are those developed to fit the LCD data sets such as IPT and CIELAB. Most colour difference formulae such as CMC, CIE94, BFD, CIEDE2000, are based on the modification of the CIELAB without an associated uniform colour spaces. CAM02-SCD and DIN99d are the colour spaces specially derived to fit the combined SCD data.

Overall, CAM02-LCD and CAM02-SCD outperformed the other colour spaces. They should be integrated into CIECAM02 for evaluating large and small colour differences.

3.2 Qualitative Comparison Between Newly Developed Models

A comparison was made to reveal the different scales imbedded in CIECAM02, CAM02-LCD and CAM02-SCD. During the development of the new spaces, it was found that a consistent improvement of 2 PF/3 units occurred for all data sets from *J* to *J'* scale. It was thus decided to use *J'* in the two new spaces. In general, the *J'* values are about 20% higher than *J*, with a maximum difference about 30% at *J* of 43.

Comparing between *M* and *M-SCD,* and between *M* and *M-LCD* colourfulness scales, it revealed that *M-LCD* and *M-SCD* scales predicted values are slightly lower and much lower than those of *M* scale, respectively. In addition, both new spaces show an expansion of *M* scale for low colourfulness colours and a compression for high colourfulness colours. However, a much larger extent of the above trend was found for small colour differences than the large colour differences. This was also found earlier[5] that the largest discrepancy between the large and small colour differences is in the chroma attribute.

3.3 Qualitative Comparisons Between New and The Other Colour Spaces

The two new colour spaces were further compared with the others. For LCD data, the OSA data with $L_{OSA}=0$ are plotted in CIELAB, IPT, CIECAM02 and CAM02-LCD as shown in Figure 1a to 1d, respectively. The samples form a structure of grids. For a perfect agreement between the data and space, these grids should be equal-sized squares.

The results show that the grids in CIELAB space (Figure 1a) are not squares and have some variations in sizes, e.g. large differences between yellow with blue regions. The IPT space (Figure 1b) in general gives a good fit to the data, i.e. the sizes of all grids are more or less equal to each other. This is due to the space was fitted to this set of data. For CIECAM02 (Figure 1c), all grids are more or less followed the vertical and horizontal directions with similar size. However, the grids close to neutral are larger than those in high chroma regions. This means that the CIECAM02 predicted a larger colour difference than the OSA data for colours close to neutral. This trend is even more obvious in Figure 1d for the new CAM02-LCD. This implies that there are some discrepancies between the OSA and the other LCD data sets in the neutral region because CAM02-LCD was developed to fit all six LCD data sets.

For comparing different colour spaces for SCD data, the experimental ellipses used in the previous studies[8] are plotted in CIELAB, DIN99d, CIECAM02 and CAM02-SCD as shown in Figures

2a to 2d. The size of each ellipse was adjusted by a single factor in each space to ease visual comparison. For a perfect agreement between the experimental results and a uniform colour space, all ellipses should be constant radius circles.

Overall, it can be seen that the ellipses in CIELAB and CIECAM02 spaces are smaller in the neutral and gradually increase in size when colourfulness increases. Also, the ellipses are orientated more or less towards the origin except for those in the blue region at CIELAB space. All ellipses in CAM02-SCD are more or less equal sized circles. It performed even better than DIN99d as its ellipses are very large close to neutral comparing with the other regions. For evaluating small colour-differences, CIE is currently recommending CIEDE2000, which does not have an associated colour space. The results in Table 1 showed that CAM02-SCD performed only slightly worse than CIEDE2000 by one PF/3 unit and has associated uniform colour spaces.

4. TESTING NEW SPACES USING ILLUMINANT A DATA

Another severe test of colour difference equations or uniform colour spaces was also carried out to use experimental data[10] under the viewing conditions largely disagreed with those recommended by CIE[16]. One set of data accumulated at the University of Bradford under Illuminant A is suitable for this test. The testing results are also given in Table 1. It includes 1053 textile pairs with an average CIELAB about 3 units. Each pair was assessed by a panel of 20 observers.

It can be seen that CAM02-SCD performed the second best amongst all the models tested. The BFDA[10] formula performed the best as expected because it was derived to fit this particular set of data. The results demonstrated a great advantage to have a universal colour model based on CIECAM02 colour appearance model, which is capable of transforming colour stimuli under different viewing parameters such as illuminant, luminance level, lightness of backgrounds and surrounds into a reference set of viewing conditions as the reference viewing conditions suggested by CIE[16]. Subsequently, the colour differences can be calculated. Note that almost all colour difference equations were developed for daylight illuminants.

5. CONCLUSION

This paper described an extension of the CIECAM02 for evaluating colour differences. The results clearly show that the two extended spaces, CAM02-LCD and CAM02-SCD, outperformed the other uniform colour spaces in predicting large and small colour differences, respectively. The latter also gave the best prediction to a set of data accumulated under illuminant A. This demonstrates that a major advantage over the conventional colour difference formulae or spaces, which can only be applied under a set of reference viewing conditions. The present results proved that a reliable colour appearance model can be expanded to perform all colorimetric applications such as specifying colour, predicting colour appearance and evaluating colour-differences.

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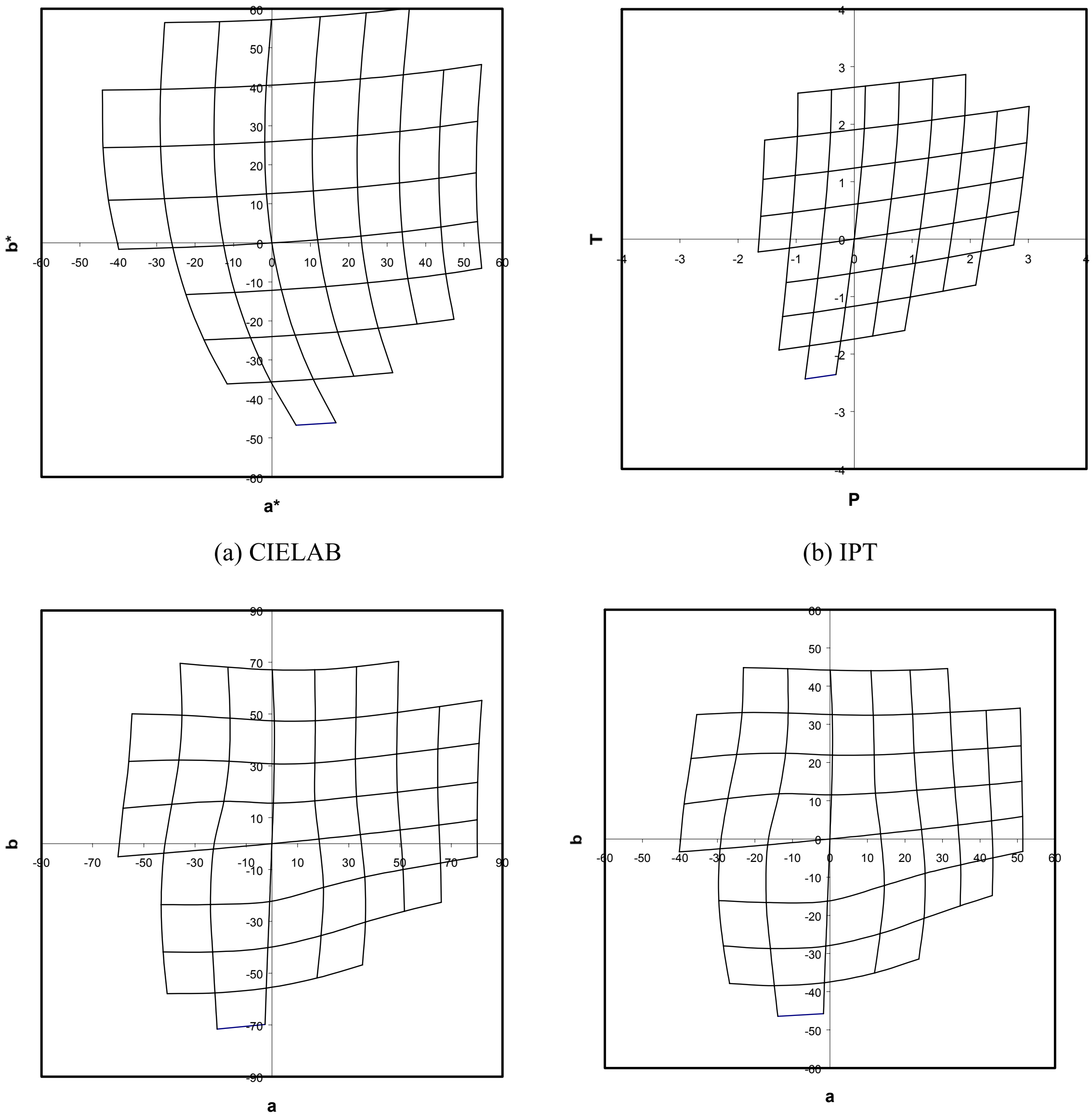

(a) CIELAB (b) IPT

(c) CIECAM02 (d) CAM02- LCD

Figure 1: OSA data with L=0 plotted in a) CIELAB, b) IPT, c) CIECAM02 and d) CAM02-LCD

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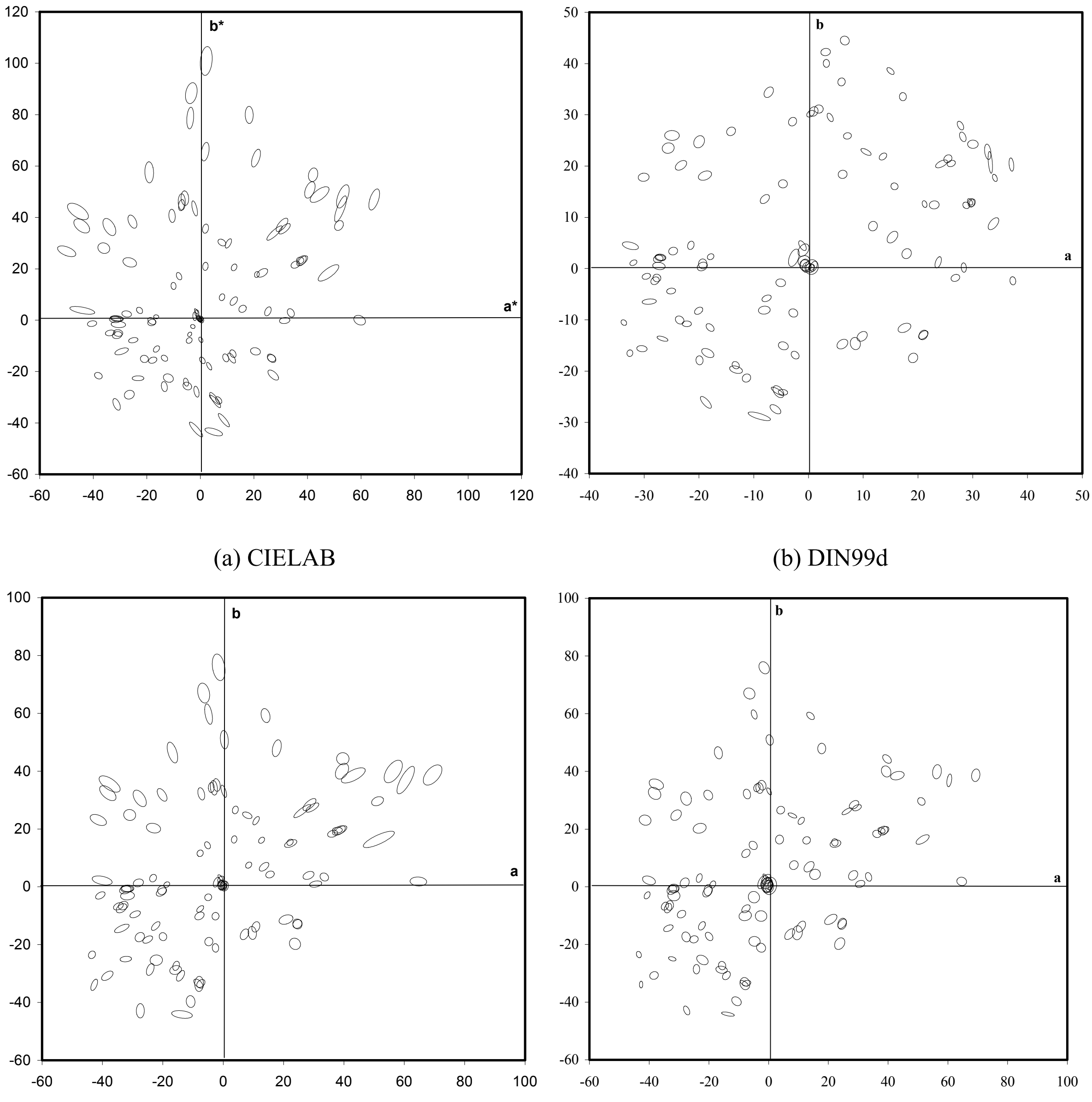

(a) CIELAB (b) DIN99d

(c) CIECAM02 (d) CAM02-SCD

Figure 2: Experimental chromatic discrimination ellipses plotted in a) CIELAB, b) DIN99d, c) CIECAM02 and d) CAM02-SCD