Colour-Differences Evaluation Using Colour Appearance Models

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Abstract

Colour appearance models (CAM) such as CIECAM97s and CIECAM02 were originally developed to predict the change of colour appearance under different viewing conditions. This paper describes the development of CAM extensions for evaluating colour–differences. The performances of the original CAMs and their extensions were tested using two types of colour-difference data: large and small magnitude colour-differences. The results showed that the CIECAM02 based models in general gave a more accurate prediction than the CIECAM97s based models. The modified version of CIECAM02 gave satisfactory performance in predicting different data sets (better than or equal to the best available uniform colour spaces and colour- difference formulae). This strongly suggests that a universal colour model based upon a colour appearance model can be achieved for all colorimetric applications: colour specification, colour difference and colour appearance.

Introduction

Colour appearance and colour-difference are conventionally different research fields. Over the years, separate colorimetric models have been developed to fit completely different types of data: colour appearance models and colour difference formulae. However, earlier work by Luo *et al*[1] demonstrated that using a single model it is possible to obtain reasonable predictions to both colour appearance and colour-difference data sets. In 1997, the CIE recommended an interim colour appearance model, CIECAM97s[2] for predicting corresponding colour appearance to achieve cross-media colour image reproduction. In 2002, CIECAM02[3] was recommended by CIE TC8-01 and is a revision of CIECAM97s in order to improve the performance and also to simplify the model. Both models were tested using two distinct types of colour-difference data sets as found by Zhu *et al*[4,5]: large and small colour-difference data sets, designated as LCD and SCD respectively. The LCD data includes six subsets: CII-Zhu,[6] OSA[7] Guan,[8] BADB-T,[9] Pointer[10] and Munsell.[11,12] They have 144, 128, 292, 238, 1038 and 844 pairs respectively and CIELAB[13] colour-difference values ranged from 9 to 14 with an average of 10. The SCD data used in this study is the combined data set used to derive the current CIE colour-difference formula, CIEDE2000,[14] and DIN99d[15] colour space. It includes 3652 sample pairs with an average of 2.5 CIELAB ΔE units. Various colour spaces and colour-difference formulae based upon CIECAM02 and CIECAM97s were derived by fitting LCD and SCD data. Their performances were compared against some of the best previously published colour difference formulae and uniform colour spaces.

Testing the Performances of CIECAM97s and CIECAM02

As mentioned earlier, six LCD and one SCD data sets were accumulated. They were used to test the performances of CIECAM97s and CIECAM02. Zhu *et al*[4] found that the Munsell data behaved very differently from the other five LCD subsets. This was caused by the incorrect balance between the lightness and chromatic differences in the data, i.e. all earlier work[16,17] assumed a ratio of 1:2 (one Munsell Value step appear to have equal colour difference as two Munsell Chroma steps). Zhu et al found a ratio of 1:1.25. This was further corrected to 1:3 in a later study.[5] Once this relation is built into the Munsell data, it has a very similar characteristic to the other five LCD data sets. This is the latest version of the Munsell data used in the current study.

CIECAM97s and CIECAM02 involve the attributes: brightness *(Q),* lightness *(J),* colourfulness *(M),* chroma *(C),* saturation *(s),* hue composition *(H),* and hue angle *(h).* For constructing a uniform colour space, three of the possible combinations are frequently used: *J,M,h; J,C,h and J,s,h.* Note that hue composition expresses the amounts of unitary hues (red, yellow, green and blue) and is typically used for describing colour appearance, not for evaluating colour difference. The colour difference for each of the three spaces is calculated using equation (1).

$$\Delta E = \sqrt{\Delta J^2 + \Delta a_V{}^2 + \Delta b_V{}^2} \qquad (1)$$

where $a_V = V\cos(h)$, $b_V = V\sin(h)$ and V represents the M, C or s attribute for CIECAM97s and CIECAM02.

Table 1. The performance of the six CIECAM COLOUR SPACEs

Dataset \ Space	CIECAM97s	CIECAM97s	CIECAM97s	CIECAM02	CIECAM02	CIECAM02
	J, a_C, b_C	J, a_M, b_M	J, a_s, b_s	J, a_C, b_C	J, a_M, b_M	J, a_s, b_s
CII-Zhu	37	36	57	30	**29**	64
OSA	26	26	33	22	**21**	37
GUAN	37	35	57	27	**24**	44
BFD-Textile	35	34	58	31	**29**	43
Pointer	40	39	51	36	**35**	55
Munsell	41	39	73	31	**28**	48
LCD Average	35	34	54	28	**27**	49
SCD	48	46	88	49	**47**	78

These six uniform colour spaces were tested using all the LCD and SCD data sets. The PF/3 measure[8] is again used to indicate the performance. For perfect agreement, PF/3 should be zero. A PF/3 value of 30 means a 30% disagreement between a model's prediction and visual data. The performance of the models tested for each data are summarised in Table 1 together with the average from all six LCD data sets (LCD Average).

It can be clearly seen that CIECAM02 J,a_M,b_M performed slight better than CIECAM02 J,a_C,b_C. Both spaces outperformed the other spaces by a large margin. In general, CIECAM02 spaces outperformed CIECAM97s spaces. Also, the spaces developed from the saturation scales performed the worst. Comparing the new spaces with the best colour-difference formulae or uniform colour spaces available in the LCD category, it is quite encouraging that CIECAM02 J,a_M,b_M performed very well with 27 PF/3 units for LCD average comparing with 30, 25 and 23 units for CIELAB,[13] IPT[18] and GLAB,[8] respectively. However, CIECAM02 J,a_M,b_M predicted the SCD data (47 units) much less accurately than CIEDE2000 (33) and DIN99d (35). This implies that there is a large different characteristic between the LCD and SCD data.

Developing CIECAM based Colour-Difference Formulae and Uniform Colour Spaces

Following a similar strategy as in our earlier work,[4,5] new colour-difference formulae and uniform colour spaces based upon CIECAM02 and CIECAM97s were developed. The first model developed is a colour-differrence formula (not a uniform colour space) which has a general structure given in equation (2), for which the tolerances at a particular point in colour space are commonly represented with an ellipsoid.

$$\Delta E = \sqrt{\left(\frac{\Delta J}{k_J(1+\beta_J \overline{J})}\right)^2 + \left(\frac{\Delta M}{k_M(1+\beta_M \overline{M})}\right)^2 + \left(\frac{\Delta H}{(1+\beta_H \overline{M})}\right)^2}$$
$$\text{where}$$
$$\Delta J = J_1 - J_2, \quad \Delta M = M_1 - M_2, \quad \Delta H = 2\sqrt{M_1 M_2}\sin(\Delta h/2) \qquad (2)$$
$$\text{and}$$
$$\overline{J} = (J_1 + J_2)/2, \quad \overline{M} = (M_1 + M_2)/2$$

The k_J, β_J, k_M, β_M and β_H are coefficients were optimised to give the best fit to the experimental data sets in terms of the PF/3 measure. Equation (2) includes five coefficients, which were optimised by modifying CIECAM97s or CIECAM02. The β_J, β_M and β_H coefficients here are set to be nonnegative. If they are negative, it is possible that the whole term could be zero, which leads to a breakdown of calculation. The new colour-difference formulae are named CAM97-LCD5CDE and CAM02-LCD5CDE, and CAM97-SCD5CDE and CAM02-SCD5CDE for LCD and SCD applications respectively.

New colour spaces having the structure of equation (3) were also developed. All three original spaces (*J,M,h, J,C,h, J,s,h*) were modified. It was again found that the *J,M,h* space fitted the best to the various data sets. Hence, only its results are reported here. The input values are in a polar space: lightness *(J)*, colorfulness *(M)* and hue angle *(h)*. These were then transformed to Cartesian coordinates, *J*, *a'* and *b'* (see equation (3)). The two coefficients, k_J *and* β_M, were obtained by minimising the PF/3 values to fit the experimental data sets. Again, the coefficients are always positive. The extended CIECAM97s spaces are named CAM97-LCDUCS and CAM97-SCDUCS for LCD and SCD applications respectively. Similarly, CAM02-LCDUCS and CAM02-SCDUCS were derived from CIECAM02.

The same technique to derive the above formulae and spaces was also applied to CIELAB and IPT to improve their performances to fit the same data sets. This results in CIELAB-LCD5CDE and IPT-LCD5CDE, and CIELAB-SCD5CDE and IPT-SCD5CDE for LCD and SCD applications respectively.

$$\Delta E' = \sqrt{\Delta J^2 + \Delta a'^2 + \Delta b'^2}$$
$$\text{where}$$
$$\Delta J = J_1 - J_2, \quad \Delta a' = a'_1 - a'_2, \quad \Delta b' = b'_1 - b'_2 \qquad (3)$$
$$\text{and}$$
$$M'_1 = (k_J/\beta_M)\ln(1+\beta_M M_1), \quad M'_2 = (k_J/\beta_M)\ln(1+\beta_M M_2),$$
$$a_1' = M'_1\cos(h_1), \quad b_1' = M'_1\sin(h_1),$$
$$a_2' = M'_2\cos(h_2), \quad b_2' = M'_2\sin(h_2)$$

Finally, it was found that the models based on equation (3) can be further improved by adopting a new lightness scale (*J'*) as given in equation (4).

$$J' = \frac{1.7J}{1 + 0.007J} \quad (4)$$

This new formula was obtained by fitting all the available data sets. The modified colour spaces are designated as CAM97-LCDUCS' and CAM97-SCDUCS', and CAM02-LCDUCS' and CAM02-SCDUCS'for LCD and SCD applications respectively.

The agreement between the newly derived models and visual data from the LCD and SCD data are summarised in Tables 2 and 3 respectively. Each model's coefficients are also listed. Some of the best models such as GLAB, DIN99d, and CIEDE2000 for each data category were also tested. Their results are also given in Tables 2 and 3.

Comparing different models' performances in Table 2 (LCD data), the results are summarised below:

- CIECAM02 based models outperformed CIECAM97s based models. This provides further evidence in favour of replacing the latter by the former.
- CIECAM02-LCDUCS' and CIECAM02-LCD5CDE outperformed the other models. It is most encouraging that they even performed slightly better than GLAB, CIE-LCD5CDE and IPT-LCD5CDE, which were solely derived as UCSs.
- For all the LCD5CDE models, their coefficients were never fully used, i.e. some of models have zero for β_J, β_M or β_H , or one for k_M coefficient. This shows that three coefficients are sufficient to fit the LCD data sets except for IPT-LCD5CDE, which requires 4 coefficients.
- Comparing CIECAM02-LCDUCS' and CIECAM02-LCD5CDE, the former is preferred because it is a uniform colour space and has a much simpler structure than the latter.

Comparing different models' performance for the SCD data (Table 3), the findings are:

- CIECAM02 based models again outperformed CIECAM97s based models.
- CIECAM02-SCDUCS' and CIECAM02-SCD5CDE gave the same performance (34 PF/3 units). They are ranked number two, only performing worse than CIEDE2000 by one PF/3 unit. It is encouraging that they even performed slightly better than CIELAB-SDC5CDE, IPT-SDC5CDE and DIN99d.
- For all the SCD5CDE models, all their coefficients were used. This shows that there is a need to have a larger modification to fit the SCD data as opposed to the LCD data.
- Comparing CIECAM02-SCDUCS' and CIECAM02-SCD5CDE, the former is preferred because it is a uniform colour space and has a much simpler structure than the latter.

Table 2. Testing uniform colour spaces and colour-difference formulae using the LCD data

Model	No. of Coef.	k_J	β_J	k_M	β_M	β_H	Average LCD (PF/3)
CAM97-LCD5CDE	5	0.28	0.0210	0.93	0.0000	0.0000	25
CAM97-LCDUCS	2	0.56	-	-	0.0001	-	27
CAM97-LCDUCS'	2	0.56	-	-	0.0001	-	25
CAM02-LCD5CDE	5	0.42	0.0180	1.00	0.0058	0.0000	**22**
CAM02-LCDUCS	2	0.77	-	-	0.0053	-	24
CAM02-LCDUCS'	2	0.77	-	-	0.0053	-	**22**
CIELAB-LCD5CDE	5	0.76	0.0000	1.00	0.0097	0.0000	23
IPT-LCD5CDE	5	0.74	0.1336	1.00	0.1853	0.0224	23
GLAB	Original						23

Table 3. Testing uniform colour sapces and colour-difference formulae using the SCD data

Model	No. of Coef.	k_J	β_J	k_M	β_M	β_H	SCD (PF/3)
CAM97-SCD5CDE	5	0.28	0.0210	0.93	0.0038	0.0000	37
CAM97-SCDUCS	2	0.56	-	-	0.0008	-	40
CAM97-SCDUCS'	2	0.56	-	-	0.0008	-	37
CAM02-SCD5CDE	5	0.54	0.0242	0.76	0.0503	0.0083	34
CAM02-SCDUCS	2	1.24	-	-	0.0363	-	37
CAM02-SCDUCS'	2	1.24	-	-	0.0363	-	34
CIELAB-SCD5CDE	5	1.20	0.0038	0.89	0.0751	0.0223	36
IPT-SCD5CDE	5	1.19	0.1889	0.86	1.5347	0.3210	35
CIEDE2000	Original						**33**
DIN99d	Original						35

In addition to the above results, the experimental ellipses used in the previous studies[14,15,19] are again used to test the performance of the different spaces. Figures 1a-1d are the plotted in the CIELAB, DIN99d, CIECAM02, and CIECAM02-SCDUCS' spaces. The ellipses sizes were adjusted by scaling factors of 1.0, 0.8, 1.1 and 1.6 for CIELAB, DIN99d, CIECAM02 and CIECAM02-LCDUCS' respectively 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 the CIELAB and CIECAM02 spaces are smaller in the neutral region and gradually increase in size when chroma 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 CIECAM02-SCDUCS' are more or less equal sized circles. They performed even better than DIN99d as its ellipses are very large close to neutral compared 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 3 showed that CIECAM02 based models performed only slightly worse than CIEDE2000 by only one PF/3 unit and have associated uniform colour spaces. They are the best uniform colour spaces available for small colour-difference applications.

Conclusion

CIE colour appearance models were extended for evaluating colour-differences in the forms of colour-difference formulae and uniform colour spaces. The results clearly show that CIECAM02 based models outperformed CIECAM97s based models. This provides further evidence that the latter should be replaced by the former. The CIECAM02 based models also performed better than or equal to the current best performing models tested using the LCD and SCD data sets. These new models should accurately estimate colour-differences under a wide range of viewing conditions. This is a major advantage over the conventional colour-difference formula, which can only be applied under high level daylight viewing conditions. The present results prove that a reliable colour appearance model can provide a universal solution to solve all colorimetric tasks such as specifying colour, predicting colour appearance and evaluating colour-differences.

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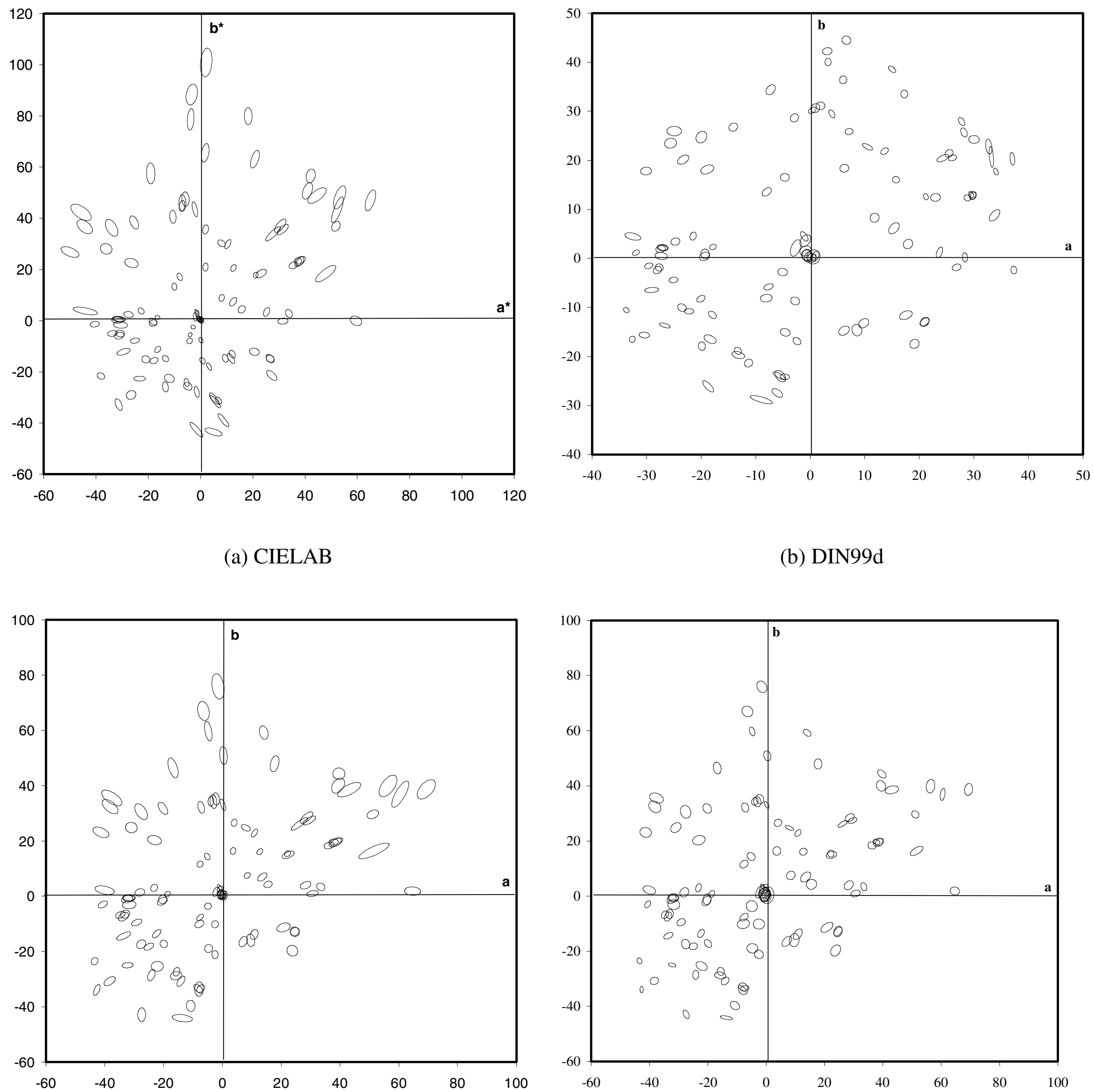

(a) CIELAB

(b) DIN99d

(c) CIECAM02

(d) CIECAM02-SCDUCS'

Figure 1. Charomatic ellipses plotted in a) CIELAB, b) DIN99d, c) CIECAM02, and d) CIECAM02-SCDUCS' spaces