Uniform Colour Spaces Based on CIECAM02 Colour Appearance Model

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Abstract: Can a single colour model be used for all colorimetric applications? This article intends to answer that question. Colour appearance models have been developed to predict colour appearance under different viewing conditions. They are also capable of evaluating colour differences because of their embedded uniform colour spaces. This article first tests 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 reasonable performance compared with the best available formulae and uniform colour spaces. It was further extended to give accurate predictions to all types of colour discrimination data. The results were very encouraging in that the CIECAM02 extensions performed second best among all the colour models tested and only slightly poorer than the models that were developed to fit a particular data set. One extension derived to fit all types of data can predict well for colour differences having a large range of difference magnitudes. © 2006 Wiley Periodicals, Inc. Col Res Appl, 31, 320–330, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20227

Key words: colour appearance model; uniform colour space; colour difference formula; colour appearance data; colour difference data

INTRODUCTION

Colorimetry has been widely used in three main application areas: colour specification, colour difference evaluation, and colour appearance prediction. Research has conventionally been conducted independently 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, the CIE recommended an interim colour appearance model,[2] CIECAM97s, for predicting corresponding colour appearance to achieve cross-media colour image reproduction. In 2002, CIECAM02 was adopted by the CIE.[3] This is a revision of CIECAM97s that improves its accuracy performance and simplifies the structure of the model. Li *et al*.[4] then tested both colour appearance models using the two distinct types of colour difference data sets accumulated by Zhu *et al*.[5] These two types are large colour difference data (LCD) and small colour difference data (SCD). They revealed that the best structure for predicting colour difference for both colour appearance models is a polar space consisting of lightness, colourfulness, and hue angle. (Note that these models include many colour correlates such as 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 can be used as a universal colour model for all colorimetric applications.

This article describes three uniform colour spaces based upon CIECAM02, which were simply modified versions to fit the LCD, SCD, and the combined LCD and SCD data sets. In addition, these new spaces were also tested using a colour difference data set under illuminant A. Currently, there is no CIE recommendation for calculating colour differences under nondaylight illuminants. The term "uniform colour space" used here is defined by the CIE[6] as a colour space in which equal distances approximately represent equal colour differences.

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EXPERIMENTAL DATA SETS

Many colour difference data sets were employed here to develop new models or to test models' performances. The LCD group includes six data sets: Zhu *et al.*,[7] OSA,[8] Guan and Luo,[9] BFDB,[10] Pointer and Attridge,[11] and Munsell.[12,13] They have 144, 128, 292, 238, 1308, and 844 pairs, respectively, and CIELAB[14] colour-difference values ranging from 9 to 14 with an average of 10. These data sets were based on not only various surface materials such as textile, ceramic, paint, and print but also CRT colours. The previous combined SCD data used to develop the CIE 2000 colour difference formula, CIEDE2000,[24] was again used to represent the SCD group. A brief account of each data set is given below.

Zhu Data

Zhu *et al.*[7] conducted a study to investigate colour discrimination for large colour difference magnitudes using CRT colours. The sample pairs were chosen along five scales in CIELAB colour space: hue, lightness, chroma, a light series, and a dark series. These included one lightness scale along the neutral axis, five chroma scales along different hue angles, eight hues with two chroma values, five mixtures of lightness and choma from white to full colour (called light series), and five mixtures from black to a full colour (called dark series). Observers were asked to adjust the spacing between each scale from two fixed ends. Finally, 144 pairs with an average 10 ΔE^*_{ab} units were accumulated.

OSA Data

The committee on Uniform Colour Scales of the Optical Society of America studied a set of large colour difference samples to construct a uniform colour space.[8] The experiment was conducted under illuminant D65 and 10° observer conditions. Forty-three colours were made in the form of 5-cm hexagonal, matte-finish, painted ceramic tiles all having approximately the same luminance factor (Y) of 30 corresponding to L^* of 62. They were assessed by 76 observers using a ratio judgement method. Sixteen other tiles that did not have the same lightness were also prepared and assessed by 49 observers. The tiles were surrounded and separated by 3–4 mm from each other by a gray card having a L^* of 62. A total of 128 perceived colour differences composed of 59 colour tiles were made and the results were then used to develop the OSA Ljg colour difference formula and its uniform colour space. The average was 14 ΔE^*_{ab} units.

Guan Data

Guan and Luo[9] selected 292 wool sample pairs from those prepared by Kuo and Luo,[15] for which 202 pairs having mainly chromatic colour differences with L^* of 50, and 90 sample pairs had mainly lightness differences using samples had either L^* of 40 or 60 against samples of L^* 50. Each pair was assessed by a panel of 10 observers twice using the gray scale method under a D65 simulator. The colour differences had an average of 11 ΔE^*_{ab} units.

BFD Badu Data (BFDB)

The Bradford Badu Data[10] were accumulated to study large colour differences. The whole data set had 238 nylon sample pairs. It can be divided into three groups: 14 neutral sample pairs having lightness differences, 130 pairs having chromatic differences at L^* of 50 plane, and the other 94 sample pairs that were mixtures of different colour differences. Experiments were carried out under a D65 simulator using the gray scale method. Each sample pair was assessed by a panel of 20 observers with normal colour vision. A total of 8160 visual assessments were made under a D65 simulator and the average ΔE^*_{ab} was 12 units.

Pointer and Attridge Data

In 1997 Pointer and Attridge[11] tested the performances of different colour difference formulae using the visual scaling of large colour differences between photographically prepared reflection colour samples at approximately constant lightness. The experimental samples consisted of 28 sets (colour centres). Each set comprised a central reference colour with up to 48 hue and chroma variations. In total, there were 1308 pairs. The average colour difference was 9 ΔE^*_{ab} units. Each pair was assessed under a D65 simulator by a panel of 9 normal colour-vision observers using the gray scale method.

Munsell Data

The Munsell data used here correspond to the physical samples used in the renotation experiment.[12] The full set of the Munsell Renotation system[13] was not used because it includes many extremely colourful and bright colours that were extrapolated from the original data set.[12] In the Munsell system each scale was designed to be visually uniform. For example, pairs having only Munsell Chroma differences (no differences in Munsell Hue and Value) should have the same visual differences. However the system itself contains no information regarding the relative sizes of the Hue, Value, and Chroma differences. The colour difference pairs were formed between the neighbouring samples along the Munsell Value, Chroma, and Hue scales. From the extensive literature survey, most of researchers assume that 2 steps of Munsell Value equal 1 step of Munsell Chroma.[16,17] However, recent evidence showed that a ratio of 3:1 is correct and this ratio is used in this study. This finding will be published elsewhere.[18] For calculating Munsell Hue differences, it assumes that the Munsell Hue and Chroma differences correspond to Euclidean space, i.e., that for a given Chroma, the sum of the Munsell Hue differences around a hue circle equals 2π times the Chroma. The Sève

TABLE I. A summary of the individual and combined LCD data sets.

Data set	No. of pairs	Weighting factor	ΔV scaling factor	Scaled pair number
OSA	128	10	3.6	1280
BFDB	238	5	1.0	1190
Guan	292	4	0.7	1168
Munsell	844	2	2.9	1688
Zhu	144	9	9.8	1296
Pointer	1308	1	1	1308
Total pairs	2954			7930

equation[19] given below was actually used for calculating hue differences.

$$\Delta H = 2\sqrt{C_{M,S}C_{M,B}}\,\sin(\Delta h/2), \tag{1}$$

where $C_{M,S}$ and $C_{M,B}$ are the Munsell Chroma values for the standard and batch in a pair, and Δh is the hue difference. Each Munsell Hue pair has the same Munsell Chroma and a constant Δh, which is 9° since 40 hue steps correspond to a full hue circle in the Munsell data.[13] The average colour difference was 10 ΔE^*_{ab} units under CIE illuminant C and CIE 1931 standard observer.

Combined SCD

The SCD data used in this study are a combined data set including four data sets: BFD,[20] RIT-DuPont,[21] Leeds,[22] and Witt.[23] These combined data were used to derive the most recent CIE recommended colour difference formula, CIEDE2000,[24] and the DIN99d[25] colour space. It includes 3657 sample pairs with an average of 2.6 ΔE^*_{ab} units.

Bradford Illuminant A Data (BFA)

Another data set[26] accumulated at the University of Bradford under illuminant A was also used to test the performance of formulae and spaces for nondaylight illuminants. It includes 1053 textile pairs with an average of 3 ΔE^*_{ab} units. Each pair was assessed by a panel of 20 observers. This unique data set can be used to verify whether the formulae developed under daylight illuminant can also predict well to the data accumulated under illuminant A.

COMBINED LARGE COLOUR DIFFERENCE DATA

In order to ease the comparison between different spaces or formulae and develop a colour space based on the available LCD data sets, the above six LCD data sets were combined to form a single data set following the same method as the combined SCD data.[24] Table I gives the number of pairs, weighting factor, ΔV scaling factor, and finally the resultant number of pairs in each data set. The Pointer data were taken as the "standard" because it is the largest data set, including 1308 pairs. A scaling factor was obtained for each data set to adjust the visual results (ΔV) on the same scale as that of the Pointer data. (It was based on the mean $\Delta E/\Delta V$ values from the available colour spaces fitted to the LCD data sets.) Finally, the weighting factor was used to duplicate the number of pairs in each data set to achieve about the same number of pairs in the combined LCD data set, including 7930 pairs in total.

NEW CIECAM02-BASED UNIFORM COLOUR SPACES

Following the same strategy as the authors' earlier work,[4,5] various 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.

Measures of Fit

Two measures were used as indicators to fit uniform colour spaces and to test various colour models. The first one is the widely used PF/3 (Performance Factor),[27] as given in Eq. (2).

$$\mathrm{PF}/3 = 100[(\gamma - 1) + V_{AB} + CV/100]/3, \tag{2}$$

where γ and CV were developed by Alder *et al.*[28] and V_{AB} by Schultz,[29] respectively. The reason for combining these measures together is for easy comparison between different models.[9,27] Sometimes different measures lead to different conclusions, e.g., one formula performed the best according to CV while the other formula gave the most accurate prediction according to V_{AB}.

For a perfect agreement between the visual results and a formula's predictions, CV and V_{AB} should equal zero and γ should equal 1. A 30% error roughly corresponds to CV of 30, V_{AB} of 0.3, and γ of 1.3. It is desirable to consider errors in percentage terms in this type of work. If one colour difference formula is identical to a second, except that it gives ΔE values twice as big, the absolute error in ΔE doubles, but the percentage error remains the same, consistent with the fact that the equations are of equal merit.

Although the PF/3 measure has been widely used, its shortcoming is that it cannot indicate the significance of difference between the two formulae or spaces tested. Hence, another measure based upon statistical F test was used. This measure was first proposed by Alman[30] in 2000 for examining 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 given in Eq. (3) was calculated differently as that original proposed[30] by removing the intercept in the equation assuming that visual difference (ΔV) and formula's predictions (ΔE) go through the origin.

(1) Define the null and alternate hypotheses (two-tailed)

H_0: $V_A = V_B$ (e.g., two formulae without significant difference)

H_A: $V_A \neq V_B$ (e.g., two formulae with significant difference)

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

$$V_M = \sum_{i=1}^{N}(\Delta V_i - a_M \Delta E_{Mi})^2/(N-1) \qquad M \in \{A,B\}. \quad (3)$$

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

where $F_C = \mathrm{F}(\mathrm{df_A}, \mathrm{df_B}, 0.975)$ is the lower critical value of two-tailed F distribution with 95% confidence level and $\mathrm{df_A}$ and $\mathrm{df_B}$ are the degrees of freedom, F_C can be found from statistical textbooks or calculated using Microsoft Excel function FINV; V_A and V_B represent the residual error variances after scaling correction for Models A and B, respectively. The a_M is calculated using $\Sigma(\Delta E_{Mi}\Delta V_i)/\Sigma(\Delta E_{Mi})^2$ (the summation over i), which is the slope between the visual results ΔV and the ΔE for Models A and B, respectively. Finally, N is the number of samples in the data set, and $\mathrm{df_A} = \mathrm{df_B} = N - 1$ in this study. The results can be divided into five categories as shown below:

- Model A is significantly better than model B when $F < F_C$;
- Model A is significantly poorer than model B when $F > 1/F_C$;
- Model A is insignificantly better than model B when $F_C \leq F < 1$;
- Model A is insignificantly poorer than model B when $1 < F \leq 1/F_C$;
- Model A is equal to model B when $F = 1$.

Modification of CIECAM02

Various modified versions of CIECAM02 were developed. The general strategy was to determine a simple model including the optimization of some model coefficients to fit different data sets. The PF/3 measure was used as the measure of fit, i.e., minimization of PF/3 using a Quasi-Newton method was carried out to obtain the best coefficients in the model until the smallest PF/3 value was reached. Finally, three spaces not only performing the most accurate but also having the simplest structure were selected. They are named CAM02-LCD, CAM02-SCD, and CAM02-UCS (uniform colour space), which were derived to fit the LCD, SCD, and combined LCD and SCD data sets, respectively. These are given in Eq. (4).

$$\Delta E' = \sqrt{(\Delta J'/K_L)^2 + \Delta a'^2 + \Delta b'^2} \qquad (4)$$

where

$$J' = \frac{(1 + 100c_1)J}{1 + c_1 J}$$

$$M' = (1/c_2)\ln(1 + c_2 M)$$

$$a' = M'\cos(h), \quad b' = M'\sin(h),$$

where J, M, h are the CIECAM02 lightness, colourfulness, and hue angle values, respectively. The $\Delta J'$, $\Delta a'$, and $\Delta b'$ are the J', a', and b' differences between the "standard" and "sample" in a pair. The K_L, c_1, and c_2 coefficients for the CAM02-LCD, CAM02-SCD, and CAM02-UCS, respectively, are given in Table II.

TABLE II. The coefficients for each version of UCS based upon CIECAM02.

Versions	CAM02-LCD	CAM02-SCD	CAM02-UCS
K_L	0.77	1.24	1.00
c_1	0.007	0.007	0.007
c_2	0.0053	0.0363	0.0228

As reported earlier,[4] the reason to adopt the J,M,h attributes in Eq. (4) is that this space gave the most accurate prediction to the experimental data sets than those based on J,C,h and J,s,h spaces, where C and s represent CIECAM02 chroma and saturation attributes, respectively. The J' formula, a simple empirical modification of the J in Eq. (4), gave a small but consistent improvement to fit all individual data sets. The M', a colourfulness scale with an origin to represent neutral colours, was derived according to the method proposed by Luo and Rigg[31] for developing a UCS to approximate the CMC colour difference formula.[32] The M' in Eq. (4), $(1/c_2)\ln(1 + c_2M)$, was derived from the typical chroma difference equation, $\Delta C^*/(1 + c_2C^*)$, in various modified CIELAB versions. It was achieved by the mathematical integration of the chroma difference equation, i.e., $\int 1/(1 + c_2C^*)dC^*$.

Comparing the Performance of the New UCSs with Some Selected Colour Models

The performances of the CIECAM02, CAM02-LCD, CAM02-SCD, and CAM02-UCS together with the best available colour difference formulae or uniform colour spaces were evaluated using the combined LCD, combined SCD, and BFA data. The test results in PF/3 units are summarized in Table III, in which each formula or space was optimized with a lightness parametric factor K_L. The comparison of different models using the BFA data will be discussed in a later stage.

Comparing different models' performances using the combined LCD data in Table III, all models gave similar performance within a PF/3 value of 4, in which CAM02-LCD and GLAB performed the best, followed by OSA. CIECAM02 having a PF/3 value of 25 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 large colour difference data sets. CAM02-SCD is given the worst performance, as expected. This again confirms that there is a large difference between the small and large colour difference data sets.

Comparing different models' performances using the SCD data in Table III, the results showed that CIEDE2000 and BFD gave similar performance and outperformed the other models. The CIEDE2000 formula is expected to perform best because it was derived to fit the SCD data. CAM02-SCD and DIN99d, which are the only available uniform colour spaces to fit the SCD data, gave similar performance as CIEDE2000. As expected, the worst models

TABLE III. Testing uniform colour spaces and colour difference formulae using the LCD, SCD, and BFA (illuminant A) data sets.

Tested using the combined LCD data sets	PF/3	Tested using the combined SCD data set (daylight)	PF/3	Tested using the BFA data set (Illuminant A)	PF/3
CIELAB[14]	26	CIELAB	52	CIELAB	52
Kuehni[33]	26	CMC[32]	38	CMC	37
SVF[34]	25	CIE94[38]	37	CIE94	35
OSA[8]	24	BFD[39]	33	BFD	35
GLAB[35]	24	CIEDE2000[24]	33	CIEDE2000	35
NCIII_C[36]	27	DIN99d[25]	35	DIN99d	34
IPT[37]	26	IPT	52	BFDA[26]	25
CIECAM02[3]	25	CIECAM02	47	CIECAM02	43
CAM02-LCD	23	CAM02-LCD	41	CAM02-LCD	37
CAM02-SCD	27	CAM02-SCD	34	CAM02-SCD	32
CAM02-UCS	25	CAM02-UCS	35	CAM02-UCS	32

Note. Each model includes an optimised K_L parametric factor.

are those developed to fit the LCD data sets such as IPT and CIELAB. Most colour difference formulae (such as CMC, CIE94, BFD, and CIEDE2000) gave reasonable predictions but they are the modified versions of the CIELAB without an associated uniform colour space.

Overall, CAM02-LCD and CAM02-SCD outperformed most of the other colour spaces for the LCD and SCD data, respectively. It is also very encouraging that CAM02-UCS developed to fit the LCD and SCD data sets also gave excellent performance in predicting both data sets, i.e., it performed only slightly poorer than CAM02-LCD by 2 PF/3 units for LCD data and poorer than CAM02-SCD by 1 PF/3 unit for SCD data. When selecting one UCS to fit colour differences across a whole range, CAM02-UCS can be a suitable candidate.

The F test was also carried out and the results are given in Tables IV and V for the combined SCD and combined LCD data, respectively. Note that in each table, the corresponding values above the diagonal are the inverse of the values under the diagonal.

In Table IV, the F_C and $1/F_C$ critical values for the SCD data set in Eq. (3) are 0.937 and 1.067, respectively. Looking at the data in each row of the CIEDE2000 and BFD models, the F values in 14 of 15 cases are smaller than 0.937, indicating that both models significantly outperformed the other models by a very large margin. The CAM02-SCD and DIN99d performed only slightly more poorly than CIEDE2000 and BFD. These four models are expected to perform better because they were developed to fit the SCD data set. It can also be found that the models fitted to the LCD data sets performed much more poorly than those fitted to the SCD data such as NCIII_C, IPT, Kuehni, SVF, OSA, and CIELAB. It is encouraging that the models developed here CAM02-SCD outperformed the other models except CIEDE2000 and BFD. Furthermore, CAM02-UCS performed slightly more poorly than CAM02-SCD and gave a similar performance to the DIN99d and CIE94 formulae, which were specially developed to fit small colour difference data.

In Table V, the F_C and $1/F_C$ critical values for the LCD data set in Eq. (3) are 0.930 and 1.075, respectively. It can be seen that the model developed here CAM02-LCD has 14

TABLE IV. The F test results using the combined SCD data set.

Modal B / Modal A	CIELAB	CMC	CIE94	CIEDE2000	BFD	DIN99d	CIECAM02	CAM02-SCD	CAM02-LCD	CAM02-UCS	NC_IIIC	OSA	IPT	GLAB	Kuchni	SVF	Mean
CIELAB		**1.792**	**1.836**	**2.207**	**2.295**	**1.929**	**1.138**	**2.052**	**1.463**	**1.944**	**0.937**	1.009	**0.977**	**1.325**	0.995	0.995	**1.526**
CMC	**0.558**		1.025	**1.232**	**1.281**	**1.077**	**0.635**	**1.145**	**0.817**	**1.085**	**0.523**	**0.563**	**0.545**	**0.739**	**0.556**	**0.555**	**0.822**
CIE94	**0.545**	0.976		**1.202**	**1.250**	1.050	**0.620**	**1.117**	**0.797**	1.059	**0.510**	**0.550**	**0.532**	**0.722**	**0.542**	**0.542**	**0.801**
CIEDE2000	**0.453**	**0.812**	**0.832**		1.040	**0.874**	**0.516**	**0.929**	**0.663**	**0.881**	**0.424**	**0.457**	**0.443**	**0.600**	**0.451**	**0.451**	**0.655**
BFD	**0.436**	**0.781**	**0.800**	0.962		**0.840**	**0.496**	**0.894**	**0.638**	**0.847**	**0.408**	**0.440**	**0.426**	**0.577**	**0.434**	**0.433**	**0.627**
DIN99d	**0.518**	**0.929**	0.952	**1.144**	**1.190**		**0.590**	1.064	**0.759**	1.008	**0.486**	**0.523**	**0.507**	**0.687**	**0.516**	**0.516**	**0.759**
CIECAM02	**0.879**	**1.574**	**1.613**	**1.939**	**2.016**	**1.695**		**1.803**	**1.286**	**1.708**	**0.823**	**0.887**	**0.858**	**1.164**	**0.875**	**0.874**	**1.333**
CAM02-SCD	**0.487**	**0.873**	**0.895**	**1.076**	**1.119**	0.940	**0.555**		**0.713**	0.948	**0.457**	**0.492**	**0.476**	**0.646**	**0.485**	**0.485**	**0.710**
CAM02-LCD	**0.683**	**1.224**	**1.255**	**1.508**	**1.568**	**1.318**	**0.778**	**1.402**		**1.329**	**0.640**	**0.690**	**0.668**	**0.905**	**0.680**	**0.680**	1.022
CAM02-UCS	**0.514**	**0.921**	0.944	**1.135**	**1.180**	0.992	**0.585**	1.055	**0.753**		**0.482**	**0.519**	**0.502**	**0.681**	**0.512**	**0.512**	**0.752**
NC_IIIC	**1.068**	**1.912**	**1.960**	**2.356**	**2.450**	**2.059**	**1.215**	**2.190**	**1.562**	**2.076**		**1.078**	1.043	**1.414**	1.063	1.062	**1.634**
OSA	0.991	**1.775**	**1.819**	**2.187**	**2.274**	**1.911**	**1.128**	**2.033**	**1.450**	**1.926**	**0.928**		0.968	**1.312**	0.986	0.985	**1.512**
IPT	1.024	**1.834**	**1.879**	**2.259**	**2.349**	**1.974**	**1.165**	**2.100**	**1.498**	**1.990**	0.959	1.033		**1.356**	1.019	1.018	**1.564**
GLAB	**0.755**	**1.352**	**1.386**	**1.666**	**1.732**	**1.456**	**0.859**	**1.549**	**1.105**	**1.468**	**0.707**	**0.762**	**0.737**		**0.751**	**0.751**	**1.136**
Kuehni	1.005	**1.800**	**1.844**	**2.217**	**2.305**	**1.937**	**1.143**	**2.061**	**1.470**	**1.953**	0.941	1.014	0.981	**1.331**		0.999	**1.533**
SVF	1.005	**1.801**	**1.846**	**2.219**	**2.307**	**1.939**	**1.144**	**2.063**	**1.471**	**1.955**	0.942	1.015	0.982	**1.332**	1.001		**1.535**
Mean	**0.728**	**1.357**	**1.392**	**1.687**	**1.757**	**1.466**	**0.838**	**1.564**	**1.096**	**1.478**	**0.678**	**0.735**	**0.710**	0.986	**0.724**	**0.724**	

Note. Each model includes an optimized K_L parametric factor, and the F_c and $1/F_c$ critical values are 0.937 and 1.067, respectively.

TABLE V. The *F* test results using the combined LCD data set.

Modal B / Modal A	CIELAB	CMC	CIE94	CIEDE2000	BFD	DIN99d	CIECAM02	CAM02-SCD	CAM02-LCD	CAM02-UCS	NC_IIIC	OSA	IPT	GLAB	Kuehni	SVF	Mean
CIELAB		**0.473**	**0.835**	**0.820**	**0.750**	**0.751**	1.006	**0.872**	**1.200**	1.009	**0.907**	**1.106**	0.995	**1.166**	0.979	1.049	**0.928**
CMC	**2.113**		**1.765**	**1.733**	**1.584**	**1.587**	**2.126**	**1.842**	**2.537**	**2.133**	**1.916**	**2.337**	**2.103**	**2.464**	**2.069**	**2.217**	**2.035**
CIE94	**1.197**	**0.566**		0.982	**0.897**	**0.899**	**1.204**	1.044	**1.437**	**1.208**	**1.085**	**1.324**	**1.191**	**1.396**	**1.172**	**1.256**	**1.124**
CIEDE2000	**1.220**	**0.577**	1.019		**0.914**	**0.916**	**1.227**	1.063	**1.464**	**1.231**	**1.106**	**1.349**	**1.214**	**1.422**	**1.194**	**1.279**	**1.146**
BFD	**1.334**	**0.631**	**1.114**	**1.094**		1.002	**1.342**	**1.163**	**1.601**	**1.346**	**1.210**	**1.475**	**1.328**	**1.555**	**1.306**	**1.399**	**1.260**
DIN99d	**1.331**	**0.630**	**1.112**	**1.092**	0.998		**1.339**	**1.161**	**1.598**	**1.344**	**1.207**	**1.472**	**1.325**	**1.552**	**1.304**	**1.397**	**1.257**
CIECAM02	**0.994**	**0.470**	**0.830**	**0.815**	**0.745**	**0.747**		**0.867**	**1.193**	1.003	**0.901**	**1.099**	0.989	**1.159**	0.973	1.043	**0.922**
CAM02-SCD	**1.147**	**0.543**	0.958	0.941	**0.860**	**0.862**	**1.154**		**1.377**	**1.158**	1.040	**1.269**	**1.142**	**1.338**	**1.123**	**1.203**	**1.074**
CAM02-LCD	**0.833**	**0.394**	**0.696**	**0.683**	**0.624**	**0.626**	**0.838**	**0.726**		**0.841**	**0.755**	**0.921**	**0.829**	0.971	**0.816**	**0.874**	**0.762**
CAM02-UCS	**0.991**	**0.469**	**0.828**	**0.812**	**0.743**	**0.744**	**0.997**	**0.864**	**1.189**		**0.898**	**1.096**	0.986	**1.155**	0.970	**1.039**	**0.919**
NC_IIIC	**1.103**	**0.522**	**0.921**	**0.904**	**0.827**	**0.828**	**1.109**	0.961	**1.324**	**1.113**		**1.220**	**1.098**	**1.286**	**1.080**	**1.157**	**1.030**
OSA	**0.904**	**0.428**	**0.755**	**0.741**	**0.678**	**0.679**	**0.910**	**0.788**	**1.086**	**0.913**	**0.820**		**0.900**	1.054	**0.886**	0.949	**0.833**
IPT	**1.005**	**0.476**	**0.839**	**0.824**	**0.753**	**0.755**	1.011	**0.876**	**1.206**	**1.014**	**0.911**	**1.111**		**1.172**	**0.984**	1.054	0.933
GLAB	**0.858**	**0.406**	**0.716**	**0.703**	**0.643**	**0.644**	**0.863**	**0.748**	1.029	**0.866**	**0.778**	**0.948**	**0.854**		**0.840**	**0.900**	**0.786**
Kuchni	**1.021**	**0.483**	**0.853**	**0.837**	**0.766**	**0.767**	**1.027**	**0.890**	**1.226**	1.031	**0.926**	**1.129**	1.016	**1.191**		1.071	**0.949**
SVF	**0.953**	**0.451**	**0.796**	**0.782**	**0.715**	**0.716**	0.959	**0.831**	**1.144**	0.962	**0.864**	1.054	0.949	**1.111**	0.933		**0.881**
Mean	**1.134**	**0.501**	0.936	**0.918**	**0.833**	**0.835**	**1.141**	0.980	**1.374**	**1.145**	1.022	**1.261**	**1.128**	**1.333**	**1.109**	**1.192**	

Note. Each model includes an optimized K_L parametric factor, and the F_c and $1/F_c$ critical values are **0.930** and **1.075,** respectively.

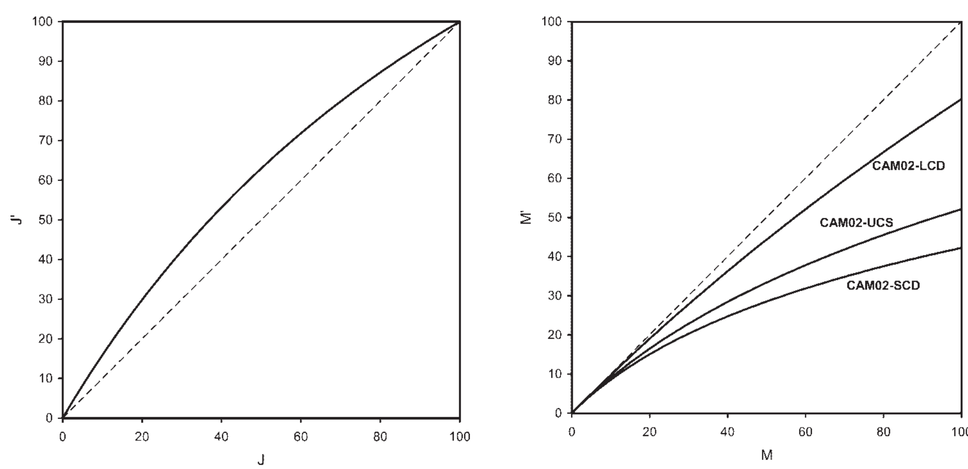
of 15 *F* values smaller than 0.930, indicating that it significantly outperformed the other models by a very large margin. It is followed by GLAB, OSA, SVF, and CAM02-UCS. The worst performance can be found for the models fitted to the SCD data sets such as CMC, BFD, DIN99d, CIEDE2000, CIE94, and CAM02-SCD.

Comparing the merits between Table III using PF/3 units and Tables IV and V according to *F* values, very similar conclusions can be drawn, i.e., CAM02-LCD and CAM02-SCD performed the best and second best for LCD and SCD data, respectively. Also, CAM02-UCS performed very close to both of them and gave an overall satisfactory prediction to the combined LCD and SCD data.

Qualitative Comparisons between Newly Developed Models

A comparison was made to reveal the different scales imbedded in CIECAM02, CAM02-LCD, CAM02-SCD, and CAM02-UCS. The first scale examined is lightness. It was found during the development of the new spaces that a consistent improvement of 2 PF/3 units occurred for all data sets from the *J* to *J*′ scale. Figure 1a is a plot of the *J* and *J*′ scales. It can be seen that there is about 20% expansion of *J*′ compared with the *J* scale, i.e., the *J*′ values are about 20% higher than *J*, with a maximum difference about 30% at *J* of 43.

The second comparison was made between *M* and its extensions (M-SCD, M-LCD, and M-UCS), as shown in Fig. 1b. It can be seen that the M-LCD, M-SCD, and M-UCS scales predicted values are smaller than the *M* scale. The former is closest to the CIECAM02 *M* scale, indicating that the colourfulness correlate of colour appearance data behaves similar to the chroma difference of the LCD data. However, the *M* scales of CAM02-SCD and CAM02-UCS are quite similar and both are largely compressed from the original *M* scale. This also confirmed our earlier study[5] that



(a) (b)

FIG. 1. The relationships (a) between *J* and *J*′ and (b) among *M*, M-LCD, M-SCD, and M-UCS. The 45° dashed lines are also plotted to show the perfect agreement between the two scales.

the largest discrepancy between the large and small colour differences is in the chroma component. For the CAM02-UCS fitted to the combined LCD and SCD data, its *M* scale is close to that of CAM02-SCD.

Qualitative Comparisons between the New and the Other Colour Spaces

The two new colour spaces were further compared with the others. The OSA data with $L_{OSA}=0$ were selected to represent the LCD group and are plotted in CIELAB, IPT, CIECAM02, CAM02-LCD, CAM02-SCD, and CAM02-UCS as shown in Figs. 2a to f, respectively. The samples form a grid structure. 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 (Fig. 2a) are not squares and have large variations in grid sizes, especially between the yellow and blue regions. The IPT space (Fig. 2b) 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 expected because the space was fitted to this set of data. For CIECAM02 (Fig. 2c), all grids more or less follow the vertical and horizontal directions with a similar size. However, the grids close to neutral have longer distances than those in higher chroma regions, i.e., CIECAM02 predicted a larger colour difference in the neutral region than the other areas, even though all perceived differences in each grid should be the same according to OSA data. This trend is even more obvious from Figs. 2d (CAM02-LCD) to e (CAM02-SCD) and f (CAM02-UCS). This implies that there are some discrepancies between the OSA data and the other five LCD data sets in the neutral region, as CAM02-LCD was developed to fit all six LCD data sets.

Comparing different colour spaces developed from the SCD data, the experimental ellipses used in the previous studies[20,40] were again used. The newly calculated ellipses are plotted in CIELAB, DIN99d, CIECAM02, CAM02-SCD, CAM02-LCD, and CAM02-UCS spaces as shown in Figs. 3a to f, respectively. 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 patterns of ellipses in CIELAB (Fig. 3a), CIECAM02 (Fig. 3c), and CIECAM02-LCD (Fig. 3e) spaces are similar, i.e., ellipses are smaller in the neutral region and gradually increase in size when chroma increases. Also, the ellipses are orientated more or less toward the origin except for those in the blue region in CIELAB space. All ellipses in CAM02-SCD (Fig. 3d) are more or less equal-size circles. It performed even better than DIN99d (Fig. 3b), as the ellipses in the neutral region are larger than those in the other regions. For evaluating small colour differences, the CIE is currently recommending CIEDE2000, which does not have an associated colour space. The results given in Table III show that CAM02-SCD performed only slightly more poorly than CIEDE2000 by 1 PF/3 unit but significant different as shown in Table IV and has an associated uniform colour space. Comparing CAM02-SCD and CAM02-UCS spaces, the patterns of ellipses appear to be very similar (see Figs. 3d and f, respectively).

TESTING NEW SPACES USING THE BFA DATA

As mentioned earlier, another severe test of colour difference equations or uniform colour spaces was carried also using the BFA experimental data[25] under illuminant A, for which the viewing condition largely disagreed with that recommended by the CIE.[38] The results in terms of PF/3 are also given in Table III.

It can be seen that CAM02-SCD performed the second best among all the models tested. The BFDA[25] formula performed the best, as expected, because it was derived to fit this particular set of data. The results demonstrated the great advantage of having a universal colour model based on the 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 similar to those suggested by the CIE.[38] These two sets of stimuli have the same colour appearance. Subsequently, the colour differences can be calculated under the reference viewing conditions. Note that almost all colour difference equations were developed for daylight illuminants.

For revealing the difference between the formulae in predicting colour differences under illuminant A, the *F* test was applied again. The results are listed in Table VI and marked with bold and italic type if the difference is significant, i.e., the *F* values fell outside the range from 0.886 (F_C) to 1.129 ($1/F_C$), the difference between two tested models is statistically significant to the 95% confidence level.

The results clearly show that the BFDA formula significantly outperformed all the other formulae and spaces. The advanced colour difference formulae derived from CIELAB are significantly better than CIECAM02 and CAM02-LCD, and all three CIECAM02 extensions are significantly better than CIECAM02 in predicting colour differences under illuminant A. The models CAM02-SCD and CAM02-UCS are better than most formulae and spaces except for BFDA.

The experimental ellipses are also plotted in CIELAB, CIECAM02, CAM02-SCD, and CAM02-UCS in Figs. 4a to d, respectively. The pattern of ellipses in CIELAB shows that all ellipses are quite long and thin and are oriented toward the origin. Also, the neutral ellipses are smaller than those in the other higher chroma regions and ellipse sizes increase when the chroma increases. The above evidence shows that CIELAB is not a UCS for the illuminant A data. For CIECAM02 ellipses (Fig. 4b), the pattern is similar to that of CIELAB except that they are more widely spread over the colour region. The patterns of CAM02-SCD and CAM02-UCS are very similar and are much closer to circles than those of CIELAB and CIECAM02. Most importantly, all ellipse sizes are very similar across all colour regions.

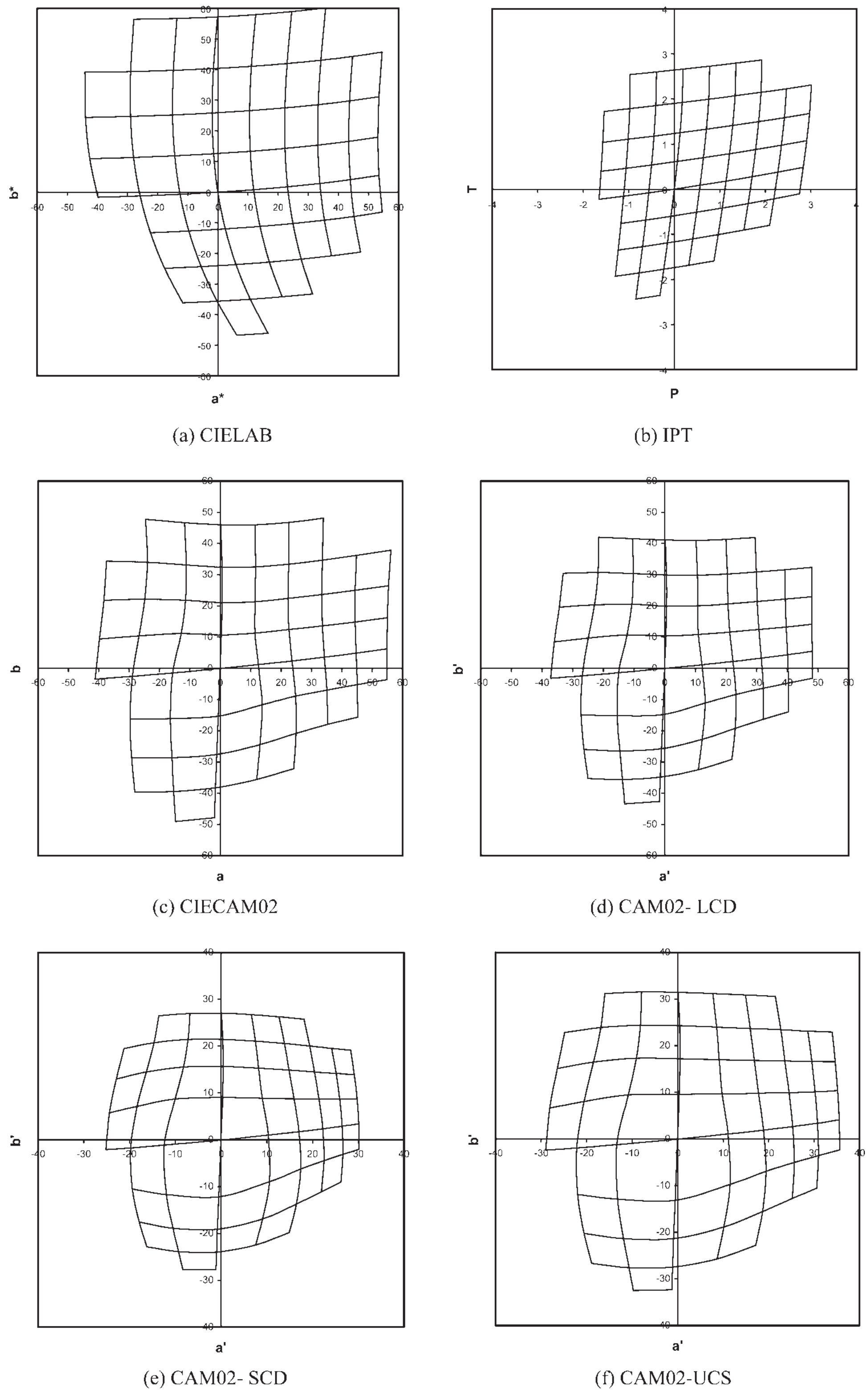


FIG. 2. OSA data with $L = 0$ plotted in (a) CIELAB, (b) IPT, (c) CIECAM02, (d) CAM02-LCD, (e) CAM02-SCD, and (f) CAM02-UCS.

The above comparisons based on experimental ellipses show that the newly developed UCSs, CAM02-SCD, and CAM02-UCS are much more uniform than CIELAB and CIECAM02.

CONCLUSION

This article described an extension of the CIECAM02 for evaluating colour differences. The results are summarized below:

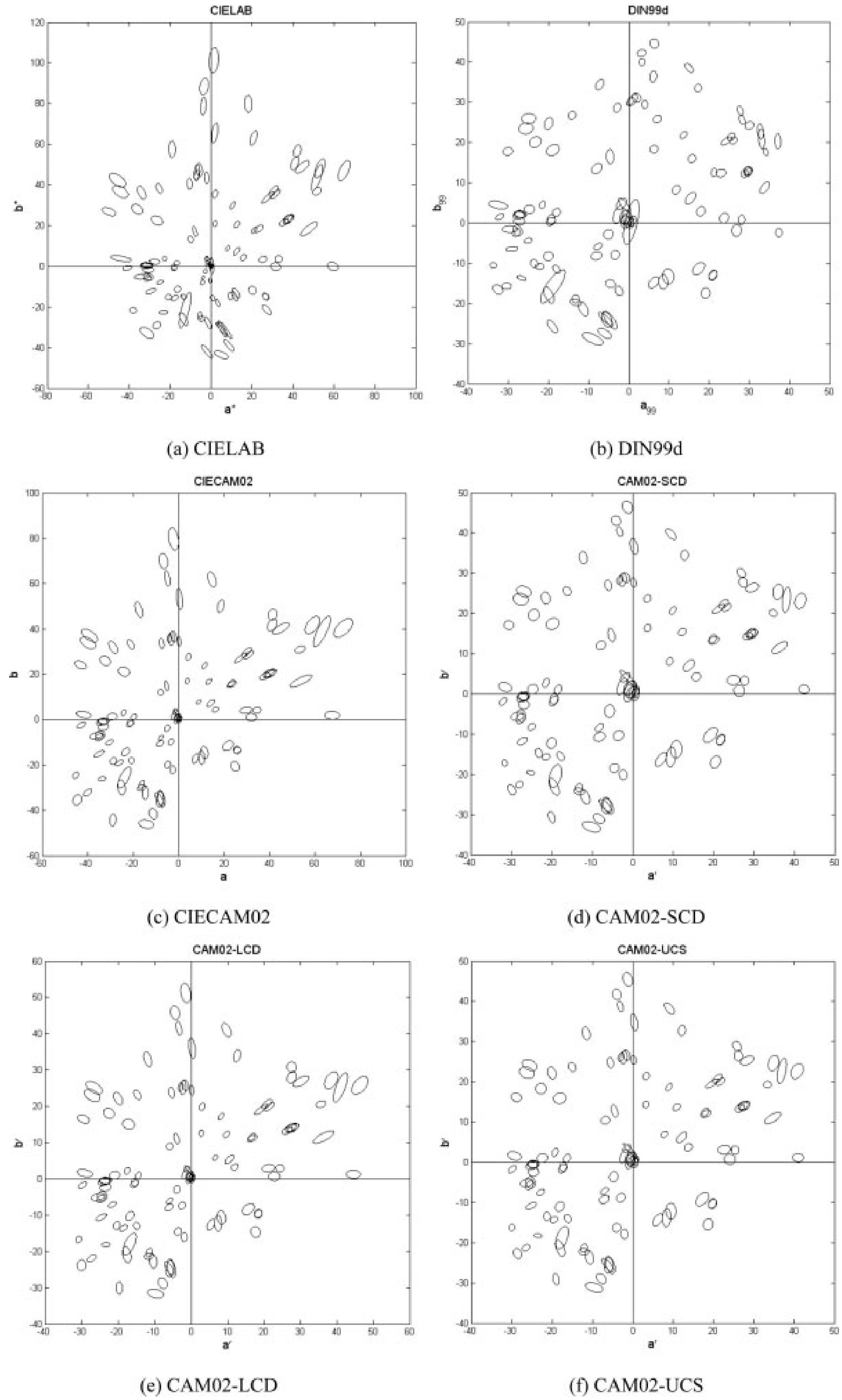


FIG. 3. Experimental chromatic discrimination ellipses plotted in (a) CIELAB, (b) DIN99d, (c) CIECAM02, (d) CAM02-SCD, (e) CAM02-LCD, and (f) CAM02-UCS.

- Three UCSs, the CAM02-SCD, CAM02-LCD, and CAM02-UCS, based on CIECAM02 colour appearance model were derived by fitting three types of data sets: LCD, SCD, and the combined LCD and SCD data sets, respectively, using the PF/3 measure.
- Compared with the other formulae and spaces, CAM02-

TABLE VI. The difference between different formulae in predicting colour difference under illuminant A.

Model A \ Model B	CIELAB	CMC	CIE94	CIEDE2000	BFD	DIN99d	BFDA	CIECAM02	CAM02-SCD	CAM02-LCD	CAM02-UCS	Mean
CIELAB		**1.921**	**2.126**	**2.264**	**2.170**	**2.267**	**3.875**	**1.381**	**2.550**	**1.798**	**2.500**	**2.285**
CMC	**0.521**		**1.107**	**1.179**	**1.130**	**1.180**	**2.017**	**0.719**	**1.327**	**0.936**	**1.301**	**1.142**
CIE94	**0.470**	0.903		1.065	**1.021**	**1.066**	**1.822**	**0.650**	**1.199**	**0.846**	**1.176**	1.022
CIEDE2000	**0.442**	**0.848**	0.939		0.959	**1.001**	**1.712**	**0.610**	**1.126**	**0.794**	1.104	0.954
BFD	**0.461**	**0.885**	0.980	**1.043**		**1.045**	**1.785**	**0.636**	**1.175**	**0.829**	**1.152**	0.999
DIN99d	**0.441**	**0.847**	0.938	0.999	0.957		**1.709**	**0.609**	1.125	**0.793**	1.102	0.952
BFDA	**0.258**	**0.496**	**0.549**	**0.584**	**0.560**	**0.585**		**0.356**	**0.658**	**0.464**	**0.645**	**0.516**
CIECAM02	**0.724**	**1.391**	**1.539**	**1.639**	**1.571**	**1.641**	**2.805**		**1.846**	**1.302**	**1.810**	**1.627**
CAM02-SCD	**0.392**	**0.753**	**0.834**	**0.888**	**0.851**	**0.889**	**1.520**	**0.542**		**0.705**	0.980	**0.835**
CAM02-LCD	**0.556**	1.068	**1.182**	**1.259**	**1.207**	**1.261**	**2.155**	**0.768**	**1.418**		**1.390**	**1.226**
CAM02-UCS	**0.400**	**0.768**	**0.851**	**0.906**	**0.868**	**0.907**	**1.550**	**0.553**	**1.020**	**0.719**		**0.854**

Note. Each model includes an optimized K_L parametric factor, and the F_c and $1/F_c$ critical values are **0.886** and **1.129,** respectively.

LCD and CAM02-SCD performed either the best or close to the best model at predicting the LCD and SCD data, respectively.

- The testing results of the models' performances based on PF/3 and F values lead to very similar conclusions.
- The results also revealed systematic variations between the colour appearance data and colour difference data in lightness and chroma (or colourfulness) directions.
- Comparing models' performances using BFA data set, although the BFDA formula performed best, it is re-

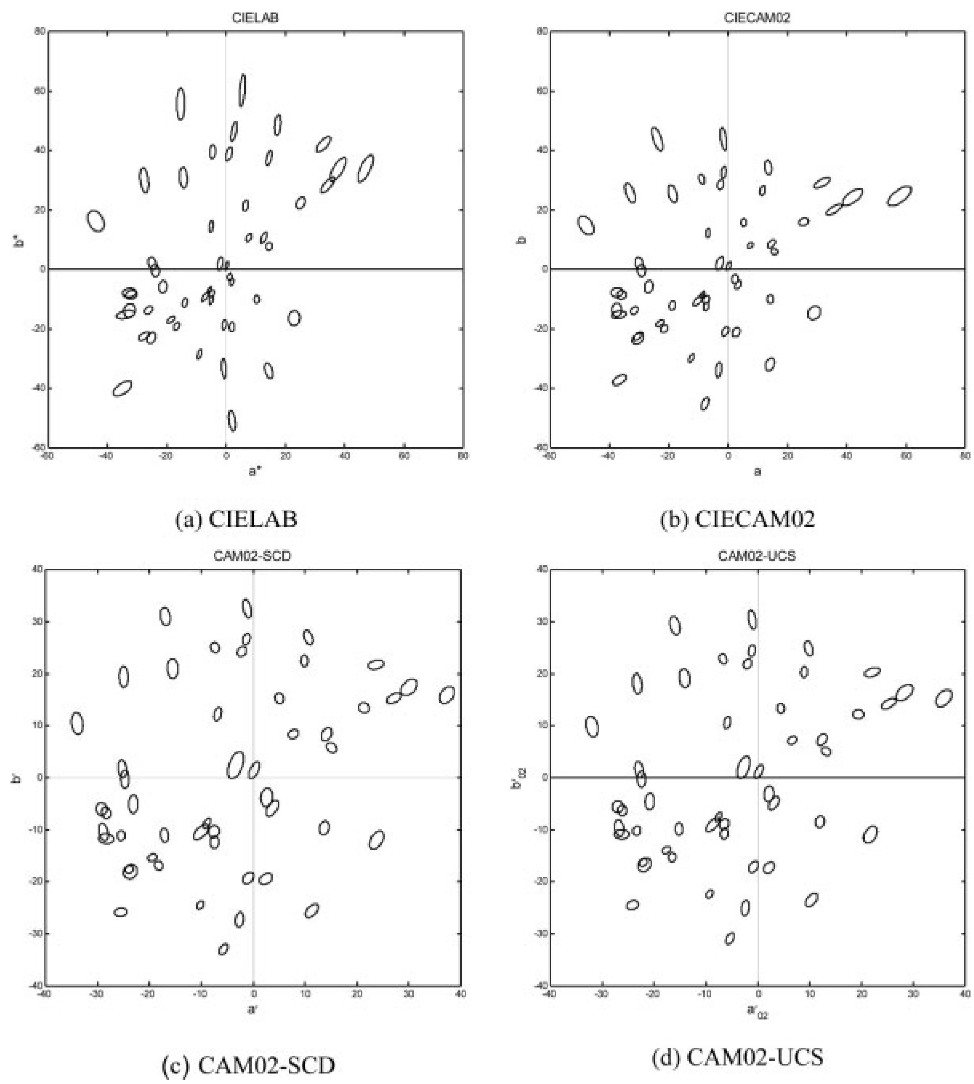


FIG. 4. Experimental chromatic discrimination ellipses under illuminant A plotted in (a) CIELAB, (b) CIECAM02, (c) CAM02-SCD, and (d) CAM02-UCS.

stricted for use under illuminant A and does not have an associated colour space. Again, CAM02-SCD and CAM-UCS performed the second best.

- Comparing performances of formulae or spaces, the earlier experimental ellipses were plotted in various UCSs. The results clearly showed that most of ellipses in CAM02-SCD and CAM02-UCS are close to constant sized circles.
- It is encouraging that CAM02-UCS (developed to fit both LCD and SCD data sets) gave a satisfactory performance, i.e., only slightly poorer than the CAM02-LCD and CAM02-SCD for the LCD and SCD data, respectively. Most importantly, it can be used for applications including colour differences ranging from small to large magnitudes such as the colour reproduction in the graphic arts industry.

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