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A Colour Appearance Model based on $J_za_zb_z$ Colour Space

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Abstract

The current CIE colour appearance model CIECAM02 and its variant named CAM16 can well predict common colour appearance attributes including lightness, brightness, chroma, colourfulness, saturation, hue angle, and hue composition. These models are complicated as well as have mathematical problems. The current study aimed a new colour appearance model based on $J_za_zb_z$ color space to obtain either better or similar performance compared with CAM16 but the new model should be computationally simple and robust. Such a model will particularly be suitable for color management in high dynamic range and wide color gamut applications. A range of experimental data were collected and a set of equations was derived. Some initial test results are presented in this paper.

Introduction

A simple colour appearance model has long been desired for colour management systems. The International Commission on Illumination (CIE) recommended CIECAM02 in 2004 [1]. A revision of CIECAM02 has recently been proposed to overcome its mathematical problems to avoid any computational failure during image processing and was named CAM16 [2]. CAM16 either gave slightly better or similar prediction performance as CIECAM02 [2]. Both CIECAM02 and CAM16 can predict seven different colour appearance attributes including Lightness, Brightness, Chroma, Colourfulness, Saturation, Hue angle and Hue Composition for related colours under the photopic region and over a wide range of viewing conditions. These models are based on empirically derived polynomials to best fit the visual data and are computationally expensive especially when large size images are to be processed. They are also limited in their scope i.e., they do not include colour scales that are commonly experienced such as Whiteness, Blackness, Vividness, Depth and Clarity [3-4]. Furthermore, they include chromatic adaptation transforms (CAT02 or CAT16) which do not well predict the experimental data [1, 2, 5].

A mathematically simple and robust colour appearance model was aimed in this study. The preliminary model proposed here includes a new two-step chromatic adaptation transform [5] to determine corresponding colours and is mainly based on a new uniform colour space [6]. It includes seven colour appearance attributes e.g., Lightness (J_z), Brightness (Q_z), Chroma (C_z), Colourfulness (M_z), Saturation (S_z), Hue angle (h_z) and Hue composition (H_z) [1,2]. Some new colour appearance attributes were also targeted e.g., Whiteness, Blackness, Depth, and Vividness [3, 4].

Zhai and Luo [5], conducted two different experiments to study neutral white and chromatic adaption in human vision and colour science and developed a new formula for degree of adaptation (D) to replace the typical D used in CAT02 and CAT16 and proposed a two-step approach for chromatic adaption transform (CAT) [5]. Secondly, in a recent study we proposed a new uniform colour space $J_za_zb_z$ [6-9] which has been tested by applying in different applications [10]. It gave the most accurate prediction performance compared with other test spaces including CIELAB, CIELUV, CAM16-UCS [2], IC_TC_P [11] and IPT [12]. The structure of $J_za_zb_z$ was similar to that of IC_TC_P except two new equations introduced to improve its perceptual uniformity in terms of Lightness, Chroma, and Hue. As $J_za_zb_z$ uses Perceptual Quantizer (PQ) function for dynamic transform of the cone responses, it can also predict perceptual lightness in high dynamic range and wide colour gamut.

Typical colour appearance attributes defined in CIE EILV [http://eilv.cie.co.at] are as follows:

Brightness (Q_z): Attribute of a visual perception according to which an area appears to emit, or reflect, more or less light.

Lightness (J_z): Brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Colourfulness (M_z): Attribute of a visual perception according to which the perceived colour of an area appears to be more or less chromatic.

Chroma (C_z): Colourfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

Saturation (S_z): Colourfulness of an area judged in proportion to its brightness.

Hue angle (h_z): Attribute of a visual perception according to which an area appears to be similar to one of the colours: red, yellow, green, and blue, or to a combination of adjacent pairs of these colours considered in a closed ring.

Hue composition (H_z): Hue composition of a colour is defined as percentage composition of two unique hues i.e., hue composition of a colour that is 80% red and 20% yellow will be R20Y.

Some new commonly used colour appearance scales were defined by Bern's [3] that will also be investigated.

The mathematical modeling of the new CAM is described in the next section followed by results and discussions. Conclusions are drawn in the end.

Modeling of the New CAM

Initially, a large set of experimental data called LUTCHI data was used [13]. These data have been previously used to develop CIECAM02 and CAM16.

Let (X, Y, Z) be the input tristimulus values of the test stimulus, (X_n, Y_n, Z_n) be the adapting white under test illuminant, (X_{nr}, Y_{nr}, Z_{nr}) be the adapting white under reference illuminant, Y_b be the background luminance factor, L_a be the test adapting field luminance, and c be the parameter to consider impact of the surround.

Step 0: Firstly compute those functions that are independent of the test stimulus.

$\alpha = 1.2 + 1.7\sqrt{\frac{Y_b}{Y_w}}$, $k = (5L_a + 1)^{-1}$,

$F_L = L_A k^4 + 0.1(1-k^4)^2(5L_A)^{1/3}$

Note that all factors computed in this step are needed for the following calculations. However, because they depend only on surround and viewing conditions, when processing pixels of an image they are computed only once. The next computing steps are sample (pixel) dependent.

Step 1: Compute (X_{D65}, Y_{D65}, Z_{D65}) i.e., tristimulus values under standard illuminant D65 using two-step chromatic adaptation transform proposed in [5].

Step 2: Calculate achromatic and chromatic channels of an opponent color space $J_z a_z b_z$ as follows:

$$\begin{bmatrix} X'_{D65} \\ Y'_{D65} \end{bmatrix} = \begin{bmatrix} bX_{D65} \\ gY_{D65} \end{bmatrix} - \begin{bmatrix} (b-1)Z_{D65} \\ (g-1)X_{D65} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.41478972 & 0.579999 & 0.0146480 \\ -0.2015100 & 1.120649 & 0.0531008 \\ -0.0166008 & 0.264800 & 0.6684799 \end{bmatrix} \begin{bmatrix} X'_{D65} \\ Y'_{D65} \\ Z_{D65} \end{bmatrix} \quad (2)$$

$$\{R' \quad G' \quad B'\} = \left(\frac{\left(c_1 + c_2 \left(\frac{\{R \quad G \quad B\}}{10000} \right)^n \right)}{\left(1 + c_3 \left(\frac{\{R \quad G \quad B\}}{10000} \right)^n \right)} \right)^p \quad (3)$$

$$\begin{bmatrix} I \\ a_z \\ b_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 3.524000 & -4.066708 & 0.542708 \\ 0.199076 & 1.096799 & -1.295875 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \quad (4)$$

where $b = 1.16$, $g = 0.7$, $c_1 = 3424/2^{12}$, $c_2 = 2413/2^7$, $c_3 = 2392/2^7$, $n = 2610/2^{14}$, and $p = 1.7 \times 2523/2^5$.

Step 3: In this step we calculate the most critical attributes including Hue angle (h_z) and Hue composition (H_z) as follows:

$$h = \tan^{-1}\left(\frac{b_z}{a_z}\right), \quad \text{where } 0 \le h \le 360 \quad (5)$$

Use the unique hue data given in table below to compute e_t and H_z. Set $h' = h + 360$ if $h < h_1$, otherwise $h' = h$. Choose a proper i (where $i = 1, 2, 3,$ or 4) so that $h_i \le h' < h_{i+1}$.

$$e_t = 1.01 + \cos\left(1.55 + \frac{h' \cdot \pi}{180}\right)$$

$$H = H_i + \frac{100 \cdot \frac{h' - h_i}{e_i}}{\frac{h' - h_i}{e_i} + \frac{h_{i+1} - h'}{e_{i+1}}} \quad (6)$$

and hue composition is computed according to H. If i=3 and $H = 241.2116$ for example, then H is between H_3 and H_4 (see Table 1 below).

Table 1. Unique Hue data for calculation of hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	33.44	89.29	146.30	238.36	393.44
e_i	0.68	0.64	1.52	0.77	0.68
H_i	0.0	100.0	200.0	300.0	400.0

Step 4: Calculate other typical Lightness (J), Brightness (Q), Chroma (C), Colourfulness (M), and Saturation (S) as follows:

$$Q = 192 \cdot (I)^{1.17} \sqrt{\frac{F_L}{c}} \quad (7)$$

$$J = 89 \cdot \left(\frac{Q}{Q_n}\right)^{0.72.c.\alpha} \quad (8)$$

$$C = \left(\frac{1}{n}\right)^{0.074} \cdot \left(a_z^2 + b_z^2\right)^{0.37} . (e_t)^{0.067} \quad (9)$$

$$M = 1.42 \cdot C \cdot F_L^{0.25} \quad (10)$$

$$s = 100 \cdot \left(\frac{M}{Q}\right)^{0.5} \quad (11)$$

Step 5: This step is about new colour appearance scales including Whiteness, Blackness and Vividness. From Cho *et al.*, [4], it was found that the Berns' proposed scales [3], Depth (D_{ab}^*), Clarity (T_{ab}^*) and Vividness (V_{ab}^*) based on CIELAB can give a reasonable fit to the data (see Equations (12)-(14)). Their results showed that D_{ab}^* had a strong positive and negative correlation to the visual saturation and whiteness data, respectively. This indicates that the two perceptions are opposite (or reverse) to each other. Vividness (V_{ab}^*) had a negative correlation to the blackness data, but unexpectedly did not fit well to Cho *et al.*'s vividness data. In contrast, Clarity (T_{ab}^*) did give reasonable prediction to the vividness data. From above analysis, we can consider Equations (12)-(14) as CIELAB-based scales for Whiteness (W), Blackness (K) and Vividness (V), respectively.

$$W_{ab}^* = 100 - \sqrt{(100 - L^*)^2 + (C_{ab}^*)^2} \quad (12)$$

$$K_{ab}^* = 100 - \sqrt{(L^*)^2 + (C_{ab}^*)^2} \quad (13)$$

$$V_{ab}^* = \sqrt{(50 - L^*)^2 + (C_{ab}^*)^2} \quad (14)$$

Similarly, three new equations for whiteness, blackness and vividness can be modeled for the new CAM and will be reported in future. The Chromaticness depends on the values of Whiteness and Blackness and can be computed using Eq. (15).

$$\text{Chromaticness} = 100 - \text{Whiteness} - \text{Blackness} \quad (15)$$

Results and Discussions

A simple colour appearance model was developed. The new model is robust because of embedded two-step chromatic adaptation transform and a uniform colour space $J_z a_z b_z$.

Firstly, LUTCHI data were used to test performance of new CAM compared with CAM16. Extended LUTCHI data consist of 7 groups (RLL, RHL, RVL, RTE, CRT, M35, LTX) where each group is divided into multiple phases based on sample size and viewing conditions [13]. Later, a data set by Juan and Luo (J&A) [14] which include data on lightness, colourfulness, hue composition and saturation was also combined with LUTCHI data by a CIE technical committee. Hence, LUTCHI data now has 8 groups of data and in total 5486 number of samples are included in the data set. Table 2 shows the prediction results for all different groups of the LUTCHI data and weighted mean of all groups in terms of Coefficient of Variation (CV). The Average (Avg) results in Table 2 show that the new CAM performed slightly better than CAM16 to predict Lightness and Hue composition while slightly worse to predict Colourfulness. Overall performance to predict LUTCHI data showed that new CAM performed equally good as CAM16.

To test and compare performance of the two different colour appearance models to predict Brightness, RVL data were used. The results in Table 3 showed that new CAM performed better compared with CAM16 to predict Brightness. Data of the RLL group (phase 6) are plotted in Figure 1(a-f) to show the trends of two different models. To test Saturation scale, Juan and Luo data were used. The results in Table 3 showed that new CAM gave better performance compared with CAM16 to predict brightness data, whereas, CAM16 gave better performance to predict saturation data. This shows that the saturation model of the new CAM needs to be further improved.

Table 2. Performance comparison of CAM16 and new CAM to predict LUTCHI data (Lightness, Colourfulness and Hue composition).

Data Sets	Lightness		Colourfulness		Hue Composition	
	CAM 16	New CAM	CAM 16	New CAM	CAM 16	New CAM
RLL	11.5	13.4	17.3	17.4	6.7	6.4
RHL	10.7	11.7	17.2	17.4	6.4	6.0
RVL	13.3	14.2	18.5	19.1	6.7	6.0
RTE	14.8	10.5	21.8	22.0	6.9	6.7
CRT	11.6	14.7	19.8	17.8	6.6	7.1
M35	19.7	17.7	16.9	19.8	7.9	7.6
LTX	16.5	12.1	15.1	17.7	5.4	4.6
J&A	14.1	13.8	19.3	17.3	6.5	6.7
Avg	**14.0**	**13.5**	**18.2**	**18.6**	**6.6**	**6.4**

Table 3. Performance comparison of CAM16 and new CAM to predict different data sets for different colour scales

Dataset	Attribute	Performance (CV)	
		CAM16	New CAM
RVL (CV)	Brightness	19.1	14.7
J&L	Saturation	19	23.3

Finally, to test performance of the attribute for Hue angle, two different data sets (Hung and Berns [15], and Ebner and Fairchild [16]) were used and results are given in Table 4 in terms of standard deviation (SD) [6]. Hung & Berns data are plotted in Figure 2(a-c) to show hue uniformity in three different spaces. Figure 2 and Table 4 showed that $J_z a_z b_z$ colour space outperformed CIELAB and CAM16-UCS especially in the blue region.

Table 4. Performance comparison of CIELAB, CAM16 and new CAM to predict Hue angle.

Attribute	Dataset	Performance (SD)		
		CIELAB	CAM16 (UCS)	New CAM
Hue Angle	Hung & Berns	3.8	4.1	2.7
	Ebner & Fairchild	3.6	4.0	2.7

Conclusions

A preliminary version of a new colour appearance model based on $J_z a_z b_z$ color space is given in this paper. The performance of the current colour appearance model was compared with CAM16 (most recent advancement in colour appearance modeling) to predict the most widely used LUTCHI data set for typical colour appearance attributes. To predict Hue angle, New CAM outperformed both CIELAB and CAM16-UCS especially in blue region. Future work also includes a more comprehensive testing and refinement of the proposed colour appearance mod.

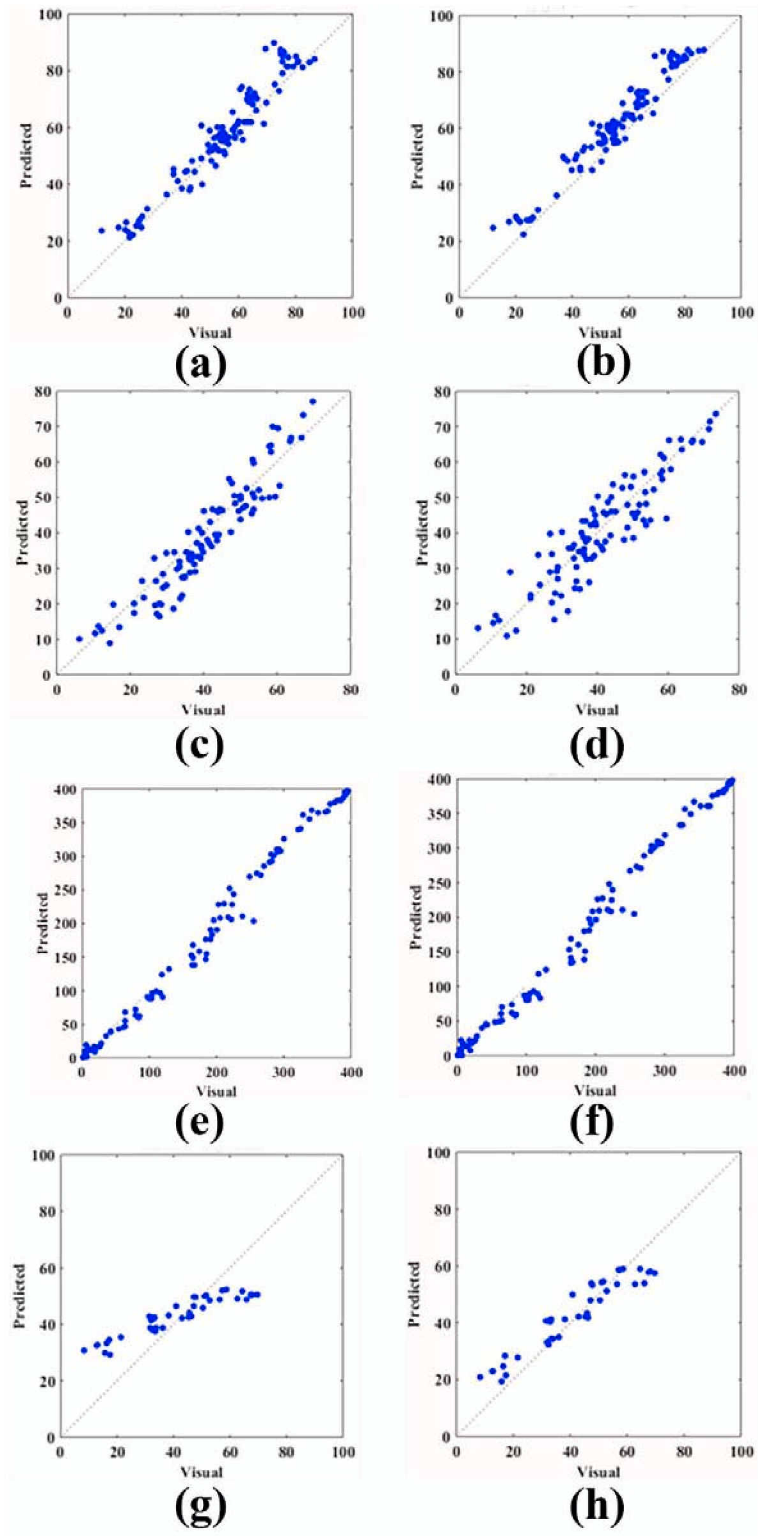

Figure 1. Plots of visual (LUTCHI) data against predictions of CAM16 and New CAM. (a-f) Group: RLL (Phase 6) and (g-h) Group: RVL (Phase 12).

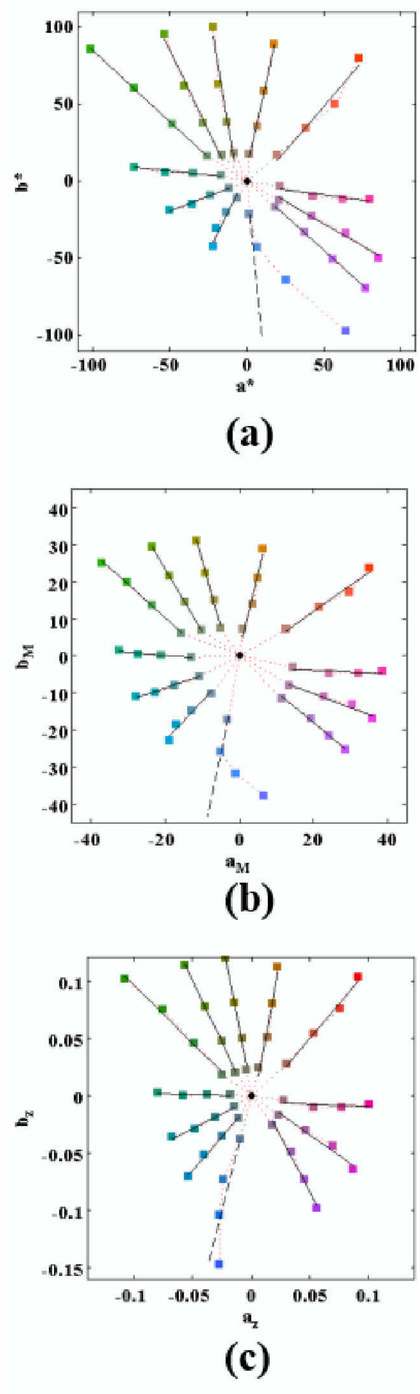

Figure 2. Hung & Berns [14] constant hue data plotted in uniform colour Spaces. (a) CIELAB, (b) CAM16-UCS, and (C) $J_za_zb_z$.

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