A Comprehensive Model of Colour Appearance for Related and Unrelated Colours of Varying Size Viewed under Mesopic to Photopic Conditions

Shou Ting Wei[1], Ming Ronnier Luo[2,3], Kaida Xiao[4] and Michael Pointer[2]

[1]Department of Visual Communication Design, TransWorld University, Yunlin, Taiwan
[2]Key State Laboratory of Modern Optical Instruments, Dept. of Optical Engineering, Zhejiang University, Hangzhou, China
[3]School of Design, University of Leeds, Leeds, UK
[4]Department of Psychological Science, University of Liverpool, Liverpool, UK

ABSTRACT

CIE has recommended two previous appearance models, CIECAM97s and CIECAM02. These models are however unable to predict the appearance of a comprehensive range of colours. The purpose of this paper is to describe a new, comprehensive colour appearance model, which can be used to predict the appearance of colours under various viewing conditions that include a range of stimulus sizes, levels of illumination that range from scotopic through to photopic, and related and unrelated stimuli. In addition, the model has a uniform colour space that provides a colour-difference formula in terms of colour appearance parameters.

Keywords: CIECAM02; comprehensive colour appearance model; uniform colour space; size effect; related and unrelated colours

INTRODUCTION

The CIECAM02 colour appearance model was published in 2002[1] superseding an earlier version, CIECAM97s[2]. Although CIECAM02 has been widely used in the graphic arts and imaging industries for cross-media colour reproduction, it is not considered as ‘comprehensive’. In the CIE 1996 Expert Symposium on Colour Standards for Imaging Technology,[3] there was extensive discussion on the necessary components of a comprehensive colour appearance model and some of these components have now been studied and the results combined with the original CIECAM02 model to provide a new ‘comprehensive’ colour appearance model that is applicable to a stimulus size up to 50°, viewing conditions that range from the mesopic to the photopic, and to both related and unrelated colours. Note that the visual angle in degrees is used here to define the size of stimulus being considered.

In 2009, the CIE established a Technical Committee, TC1-75 A comprehensive model for colour appearance. Its Terms of Reference were to derive colour appearance models that include prediction of the appearance of coloured stimuli viewed in typical laboratory conditions: 1) that appear as unrelated colours, 2) that are viewed under illumination down to scotopic levels, and 3) that include consideration of varying stimulus size.

It is well known that rods and cones are not uniformly distributed in the retina. Only cones are located in the fovea (the approximately central 1° field of the retina); outside, there are both cones and rods. In the area beyond about 40° from the visual axis, there are nearly all rods and very few cones. The rods provide achromatic vision under low luminance levels (scotopic vision) typically at luminance levels of less than some hundredths of a cd/m^2. Between this level and a few cd/m^2, where vision involves a mixture of rod and cone response, vision is referred to as mesopic. It requires a luminance of at least several cd/m^2 for photopic vision in which only cones are active. More recently, Fu et al.[4] investigated the appearance of unrelated colours for both mesopic and photopic vision using different sizes of stimuli. The results accumulated were used to develop a new colour appearance model, based on CIECAM02, with parameters to allow for the effects of luminance level and stimulus size.[4]

The first addition to CIECAM02 is the ability to estimate the colour appearance of stimuli of varying sizes under photopic vision. With advances in the displays industry, it is now possible to find displays of varying sizes from relatively small 2-3 inch mobile phone displays to 50-60 inch TV displays. There is a need to predict the associated size effect for colour appearance for accurate colour reproduction. For example, it is frequently realised that paint bought from a retail store often does not match the expectation in the real room: the appearance of the colour on the tin does not match that which is painted in the real room. CIE has published a recommendation[5] to deal with colour matching for varying stimulus sizes (and the age of the observers). This procedure is valid for stimulus sizes from 1° to 10°. Xiao et al.[6-8] investigated the issue of the appearance of stimuli of varying sizes under photopic vision and developed a CIECAM02-based model to predict the colour appearance of related colours with field sizes in the range from 2° to 50°.

The second addition to CIECAM02 is the prediction of the colour appearance of unrelated colours: an unrelated colour is a colour perceived by itself as isolated, either completely or partially, from any other colours.[9] Typical examples of unrelated colours are signal lights, traffic lights and street lights, viewed at night. These unrelated colours have very important safety implications, for example, in driving, marine navigation and airfield lighting at night.

The third addition is an extension to include the evaluation of colour (discrimination) difference. One of the earlier extensions to CIECAM02, CAM02-UCS, predicts the available colour discrimination datasets very well[10] and gives performance close to the current CIE/ISO standard colour-difference formula, CIEDE2000.[11,12] The four most reliable datasets are BFD,[13] Leeds,[14] RIT-DuPont[15] and Witt.[16]

The opportunity has also been taken to correct an error in CIECAM02. While this paper presents the construction and use of the new comprehensive model in detail, CIE TC1-96 (which succeeded CIE TC1-75 in late 2015) will write a report that outlines of the new model and a recommendation that it be used for further testing.

CORRECTION of the CHROMATIC INDUCTION FACTOR

A correction has been made to the original CIECAM02 equation for the Chromatic Induction Factor N_{cb}[1]. In an earlier study[17,18] of the colour appearance of stimuli presented against a black background, the CIECAM02 model did not well predict the colourfulness results. It is proposed to change the value of the power in the original Chromatic Induction Factor, equation (1) to that given in equation (2) to improve the performance of the model.

$$N_{cb}=0.725\ (Y_w/Y_b)^{0.2} \qquad (1)$$

$$N_{cb}=0.725\ (Y_w/Y_b)^{0.1425} \qquad (2)$$

where Y_b is the luminance factor of the background and Y_w the luminance factor of the white. The power factor of 0.1425 was found to give the best fit to both the previous LUTCHI data[19] and more recent experimental data.

SIZE EFFECT

Xiao et al.[6-8] investigated six different stimulus sizes that ranged from 2º to 50º where the same colours were assessed by a panel of observers using a colour matching method to match the target colours, displayed to one side on the wall of a room, to those on an adjacent CRT display. The colorimetric data were accumulated in terms of CIE tristimulus values measured from the wall and the display respectively. A consistent pattern of colour appearance shifts was found according to the different sizes of each stimulus. The experimental results showed that the appearance of lightness and chroma increased with the increase of the physical size of the colour stimulus, but the hue (composition) was not affected by the change of physical size of the colour stimulus. Hence, a model based on CIECAM02 for predicting the size effect was derived.

It includes four steps. Step 1 calculates the tristimulus values X, Y, Z using the CIE 2° colour matching functions under a test illuminant from a given stimulus size, θ. Step 2 predicts the appearance attributes lightness, J, chroma, C and hue, H using CIECAM02. Step 3 computes the scaling factors K_J and K_C using equations (3) and (4), respectively:

$$K_J = -0.007\theta + 1.1014 \tag{3}$$

$$K_C = 0.008\theta + 0.94 \tag{4}$$

Finally in Step 4, the colour appearance attributes J_θ, C_θ and H_θ for the target stimulus size θ are calculated using equations (5)-(7), respectively:

$$J_\theta = 100 + K_J \cdot (J - 100) \tag{5}$$

$$C_\theta = K_C \cdot C \tag{6}$$

$$H_\theta = H \tag{7}$$

Fig.1 shows the lightness, J_θ, values for three stimulus sizes (25°, 35° and 45°) plotted against lightness, J_2, values for a size of 2°. In this figure, stimulus sizes of 25°, 35° and 45° correspond to the bold solid line, the dotted line and the dashed line respectively. The thin solid line is the 45° line where $J_\theta = J_2$. The trend is quite clear, i.e. an increase in lightness for a larger stimulus size, and an associated reduction in lightness contrast. This implies that the effect increases as the lightness of the colours decreases. The opposite trend can be found for the chroma predictions, Fig. 2, where there is an increase in chroma for an increase in stimulus size. The effect is most noticeable for high chroma colours.

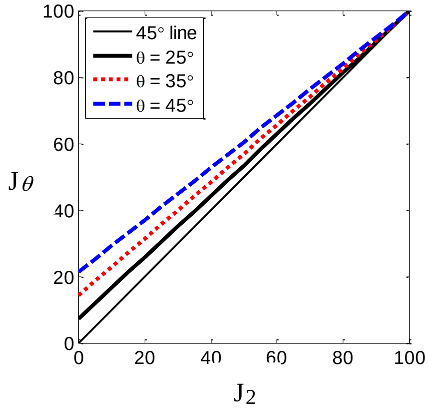


Fig. 1. The impact of stimulus size on lightness: J_θ is plotted against J_2 for $\theta = 25°, 35°, 45°$.

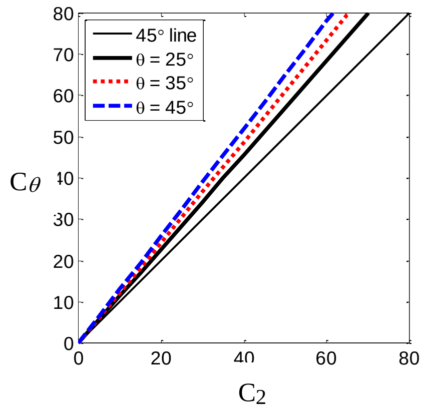


Fig. 2. The impact of stimulus size on chroma: C_θ is plotted against C_2 for $\theta = 25°, 35°, 45°$.

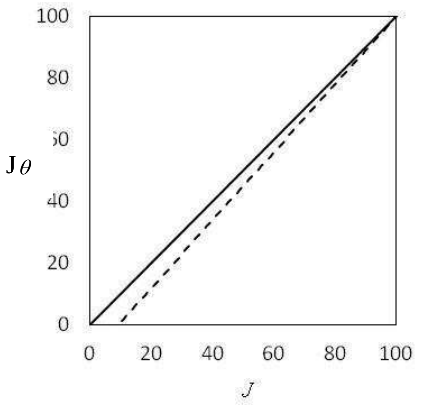


Fig. 3. The dashed line shows the relationship between J_θ and J for a 2° stimulus size. The solid line is the 45° line.

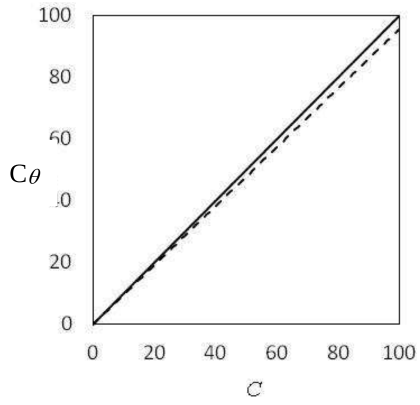


Fig. 4. The dashed line shows the relationship between C_θ and C for a 2° stimulus size. The solid line is the 45° line.

Xiao et al.[7] extended the CIECAM02 model to successfully predict the effect of stimulus size on colour appearance. However, the predictions of lightness J_θ and chroma C_θ do not match their CIECAM02 counterparts at a stimulus size of 2°. In Fig. 3 and Fig. 4, the dashed lines represent lightness, J_θ and chroma, C_θ values of the 2° field size plotted against CIECAM02 J and C values also for a 2° stimulus size, respectively. It can be seen that both dashed lines do not coincide with the 45° lines, where $J_\theta = J$ and $C_\theta = C$. In addition, negative values of J_θ can be obtained for dark colours with small sizes. For example, the value of J_θ is equal to -0.48 when $J = 7$ and $\theta = 3°$.

In order to remove the negative values of J_θ and to resolve the inconsistency between CIECAM02 and the Xiao et al. model[7] for a 2° stimulus size, a modification to the size-effect model was made.

$$J_\theta = 100 + SJ \cdot (J - 100) \tag{8}$$

$$C_\theta = SC \cdot C \tag{9}$$

where

$$SJ = \alpha_J \cdot r^2 + \beta_J \cdot r + (1 - \alpha_J - \beta_J) \tag{10}$$

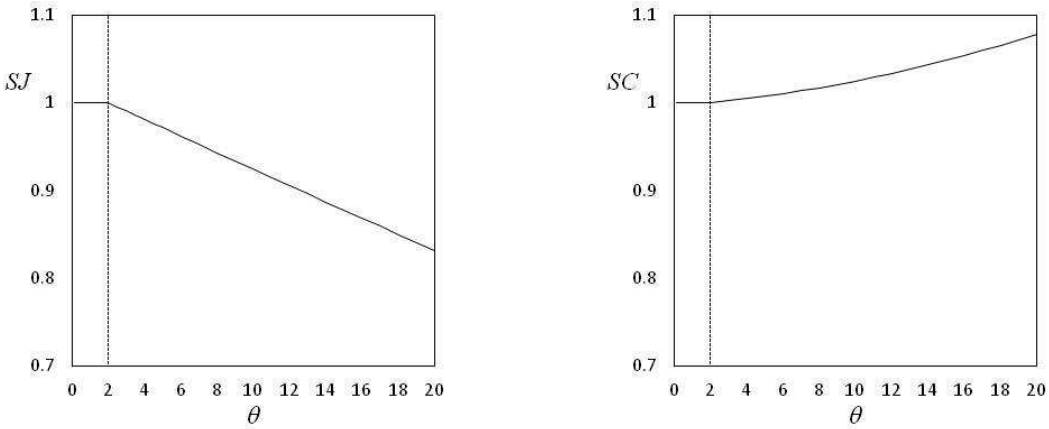
$$SC = \alpha_C \cdot r^2 + \beta_C \cdot r + (1 - \alpha_C - \beta_C) \tag{11}$$

with α_J = 0.0000437; β_J = -0.01924; α_C = 0.000513; β_C = 0.003091

and $r = \frac{\theta}{\theta_M}$ for $\theta \geq \theta_M$ (12)

$r = 1$ for $\theta < \theta_M$

where θ represents the stimulus size in degrees; θ_M is the stimulus size of either the CIE 2° or 10° standard colorimetric observer used to calculate the tristimulus values.



(a) (b)

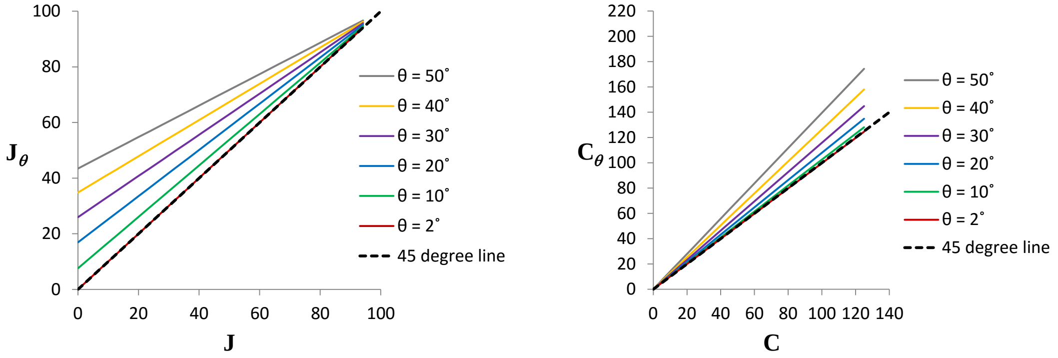
Fig. 5. (a) The relationship between the stimulus size θ and the parameter SJ for θ_M = 2°. (b) The relationship between stimulus size θ and the parameter SC for θ_M = 2°.

Figs. 5(a) and 5(b) show the relationships between the stimulus size θ and the two parameters SJ and SC for θ_M = 2°, respectively. As shown in the figures, SJ and SC are two-step functions of θ. Although the functions are not smooth, they are connected at $\theta = 2°$ to leave no gap in between.

The new size-effect model includes three features. Firstly, the size ratio (i.e. r) is used to replace the stimulus size θ in equations (3) and (4). This is to allow the size effect to be based on CIE tristimulus values calculated using not only the 2° but also the 10° standard observer. Secondly, the equations to predict the size lightness and chroma factors, SJ and SC respectively, are forced to go through the point (1, 1). This is to achieve the same output when $\theta = \theta_M$. Thirdly, rather than a linear model, a non-linear model is used to calculate the size ratio, r, to give a more accurate prediction. The predictive performance of the new model was tested using the Xiao et al. experimental data[6] which include 8°, 19°, 22°, 44° and 50° stimulus viewing sizes. Table 1 summarises the performance of the original and the modified size-effect models in terms of the Coefficient of Variation, CV: for perfect agreement, CV should have a value of zero. A CV value of 30 indicates a disagreement of 30% between two sets of data: the CV measure has been widely used in the evaluation of colour appearance models.[20] The results showed that the predictive performance of the new lightness and chroma formulae gave mostly similar or better performance, respectively, to the original size-effect model (equations (3)-(7)). Note that the complexity of equations (10)-(11) is to produce a performance not significantly worse than that of the original model and more importantly, to match their CIECAM02 counterparts at a stimulus size of 2°. Fig. 6 shows the lightness and chroma relationships between the modified size-effect model and the original CIECAM02 model for colours with different stimulus sizes.

Table 1 The model performance of the original and the new size-effect model

	CV(%)	8°	19°	22°	44°	50°	Mean
Lightness	Original model	6.6	4.0	6.2	3.8	7.6	5.6
	New model	7.5	5.7	4.4	3.8	7.8	5.8
Chroma	Original model	7.0	6.8	23.0	24.8	17.8	15.9
	New model	6.9	6.9	20.7	22.0	18.2	14.9



(a) (b)

Fig 6. Relationships between the modified size-effect model and the original CIECAM02 model in terms of (a) lightness and (b) chroma for colours with different sizes.

CIECAM02 UNIFORM COLOUR SPACE

CIECAM02 includes seven attributes in relation to a colour stimulus: lightness (J), brightness (Q), colourfulness (M), chroma (C), saturation (s), hue composition (H) and hue angle (h), in which 3 attributes (M, C, s) relate to chromatic content which, together with lightness (J) and hue angle (h), can form three possible colour spaces (J, M, h; J, C, h; J, s, h). Luo et al.[10] found that the colour space derived using J, M and h gave the most uniform performance for predicting available colour discrimination data sets. Hence, various attempts[10, 12] were made to modify this version of the CIECAM02 model to fit all available colour appearance data sets and a set of functions given in equation (13) was derived to fit the data. The space is included here because to be comprehensive a colour appearance model should include a uniform colour space to accurately predict colour differences.

$$
\begin{aligned}
J_{\mathrm{UCS}} &= \frac{1.7 \cdot J}{1 + 0.007 \cdot J} \\
M_{\mathrm{UCS}} &= \frac{\ln(1 + 0.0228 \cdot M)}{0.0228} \\
a_{\mathrm{UCS}} &= M_{\mathrm{UCS}} \cdot \cos(h) \\
b_{\mathrm{UCS}} &= M_{\mathrm{UCS}} \cdot \sin(h)
\end{aligned}
\qquad (13)
$$

where J_{UCS}, M_{UCS}, a_{UCS}, b_{UCS} are values of lightness, colourfulness, redness-greenness and blueness-yellowness in the uniform colour space, respectively.

The colour difference between two samples can be calculated in J_{UCS}, a_{UCS}, b_{UCS} space using equation (14).

$$\Delta E_{\mathrm{UCS}} = \sqrt{{\Delta J_{\mathrm{UCS}}}^2 + \Delta a_{\mathrm{UCS}}{}^2 + {\Delta b_{\mathrm{UCS}}}^2} \qquad (14)$$

where ΔJ_{UCS}, Δa_{UCS} and Δb_{UCS} are the respective differences of J_{UCS}, a_{UCS} and b_{UCS} between a standard colour and a sample (or batch) colour in a pair.

UNRELATED COLOURS

Fu et al.[4] investigated the effect of changes in the luminance level and the stimulus size on the colour appearance of unrelated colours under photopic and mesopic conditions. The observers used a magnitude estimation method to assess the brightness, colourfulness, and hue of each stimulus. Four luminance levels (60 cd/m^2, 5 cd/m^2, 1 cd/m^2 and 0.1 cd/m^2) were used. For the last luminance level, 0.1 cd/m^2, four stimulus sizes (10°, 2°, 1°, and 0.5°) were used. For the other three luminance levels, only two stimulus sizes (10° and 0.5°) were used. Each of the 50 stimuli was assessed in each of the 10 phases of the experiment. The results revealed that there is a reduction in brightness and colourfulness with decreases of both luminance level and stimulus size.

Fu et al.[4] then extended the CIECAM02 model by adding new parameters to predict the appearance of unrelated colours under both photopic and mesopic conditions. They also added a few parameters to reflect the effects of luminance level and stimulus size, as described below:

Input parameters:

Measure or calculate the luminance L and chromaticity x, y of the test colour stimulus corresponding to CIE colour matching functions (2° or 10°). The parameters are the same as for CIECAM02 except that the test illuminant is put equal to the equal energy illuminant, S_E, i.e. X_W = Y_W = Z_W = 100), L_A = 1/5 of the adapting luminance, and the surround parameters are set as for those under the dark viewing condition. As reported by Fu et al.[4], because for unrelated colours there is no reference illuminant to compare with (as there would be when assessing related colours), illuminant S_E can be used by assuming that no adaptation takes place when viewing unrelated colours.

Step 1: Use the CIECAM02 model to predict the (cone) achromatic signal A, colourfulness (M), and hue (H).

Step 2: Modify the achromatic signal A, since there is a contribution from the rod response:

$$A_{\mathrm{UN}} = A + K_A \cdot A_s \quad (15)$$

with $A_S = (2.26L)^{0.42}$ (16)

where K_A depends on the luminance level and the stimulus size defined by angle of the colour stimulus.

when $L \geq 1$ cd/m^2

$K_A = -5.3 \log_{10}(L) + 44.5$ for 0.5° stimuli (17)

$K_A = -5.9 \log_{10}(L) + 50.3$ for 10° stimuli (18)

when $L < 1$ cd/m^2

$K_A = 1.27 \log_{10}(\theta) + 22.7$ (19)

where θ is the stimulus size in degrees.

Step 3: Modify the colourfulness, M predicted from the CIECAM02 model:

$$M_{\mathrm{UN}} = K_M \cdot M \quad (20)$$

where K_M depends on the luminance level and the stimulus size of the colour stimulus.

When $L \geq 1$ cd/m^2

$K_M = 0.9$ for 0.5° stimuli (21)

$K_M = 1$ for 10° stimuli (22)

When $L < 1$ cd/m^2

$K_M = 0.1 \quad \log_{10}(\theta) + 0.27$ (23)

where θ is the stimulus size in degrees.

Step 4: Predict the new brightness:

$$Q_{\mathrm{UN}} = A_{UN} + M_{UN}/100 \quad (24)$$

Output parameters:

The required output parameters are the brightness Q_{UN}, colourfulness M_{UN} and hue composition H. Note that the hue composition H is the same as that predicted by the CIECAM02 model. The parameters K_A and K_M are defined for the stimuli at a luminance level less than 1 cd/m^2. For stimuli with a luminance level ≧1 cd/m^2, K_A and K_M are only defined for stimulus sizes of 0.5° and 10°. In Fig. 7, a θ-L plane, K_A and K_M are only defined in zone 0 and along the dashed lines that divide zones 1 and 2 and zones 2 and 3. Both parameters are not defined in zones 1, 2 and 3. In addition, there are obvious gaps in both K_A and K_M at a luminance level of 1 cd/m^2. As shown in Fig. 8, which shows the relationship between K_A and L for stimuli with a size of 10°, the gap in K_A at L equal to 1 cd/m^2 is 26.33 (i.e. 50.30–23.97). K_M also reveals a gap of 0.63 at L equal to 1 cd/m^2.

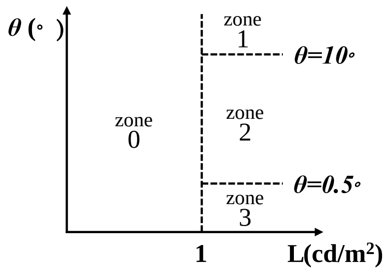


Fig. 7. A concept map showing the regions where K_A and K_M are defined.

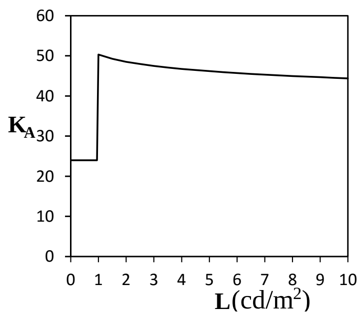


Fig. 8. The relationship between K_A and L for stimuli with stimuli size of 10°

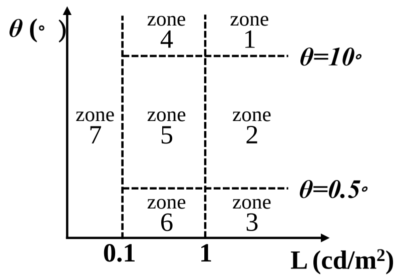


Fig. 9. The modified K_A and K_M are both divided into seven conditions, which refer to seven zones.

In order to resolve the above problems, a linear interpolation technique was used to modify the values of K_A and K_M. The modified equations are divided into seven conditions according to the seven zones defined in Fig. 9.

For L ≧1 cd/m^2,

$K_A = -5.9 \log_{10}L + 50.3$ for $\theta \geqq 10^\circ$ (zone 1)

$K_A = (0.0119\theta + 0.994)(-5.3 \log_{10}L + 44.5) + 0.0801\theta - 0.039$ for $0.5^\circ \leqq \theta < 10^\circ$ (zone 2)

$K_A = -5.3 \log_{10}L + 44.5$ for $\theta < 0.5^\circ$ (zone 3)

$K_M = 1$ for $\theta \geqq 10°$ (zone 1)

$K_M = 0.0105\theta + 0.895$ for $0.5° \leqq \theta < 10°$ (zone 2)

$K_M = 0.9$ for $\theta < 0.5°$ (zone 3)

For $0.1 \leqq L < 1$ cd/m^2,

$K_A = 1.41\,(1–L)\log_{10}\theta + 30.67L + 19.63$ for $\theta \geqq 10°$ (zone 4)

$K_A = 1.41\,(1–L)\log_{10}\theta + 0.679\,(L–0.1)\theta + 23.88L + 20.314$ for $0.5° \leqq \theta < 10°$ (zone 5)

$K_A = 1.41\,(1–L)\log_{10}\theta + 24.22L + 20.28$ for $\theta < 0.5°$ (zone 6)

$K_M = 0.11\,(1–L)\log_{10}\theta + 0.81L + 0.19$ for $\theta \geqq 10°$ (zone 4)

$K_M = 0.11\,(1–L)\log_{10}\theta + 0.012\,(L – 0.1)\theta + 0.694L + 0.201$ for $0.5° \leqq \theta < 10°$ (zone 5)

$K_M = 0.11\,(1–L)\log_{10}\theta + 0.7L + 0.2$ for $\theta < 0.5°$ (zone 6)

For $L < 0.1$ cd/m^2,

$K_A = 1.27\log_{10}\theta + 22.7$ (zone 7)

$K_M = 0.1\log_{10}\theta + 0.27$ (zone 7)

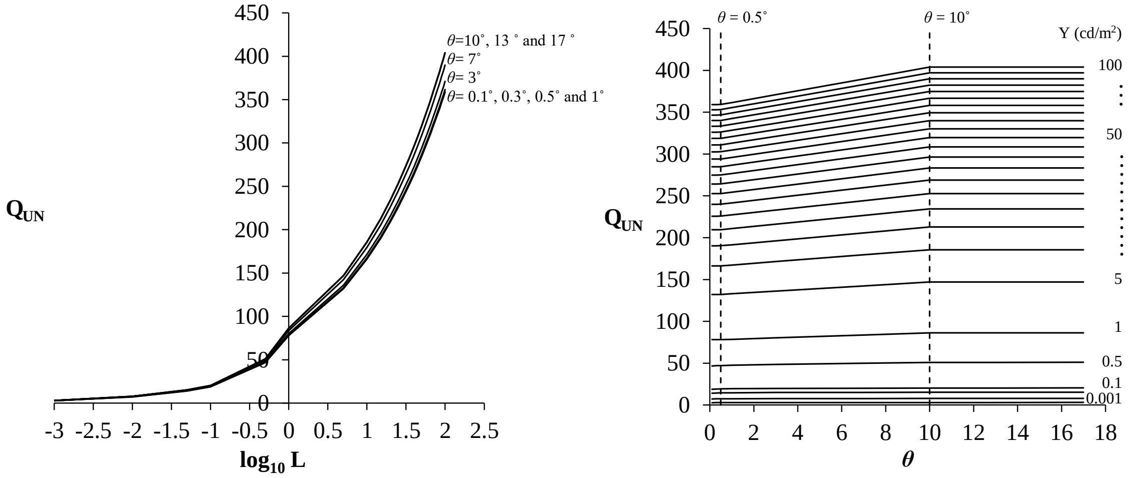


Fig. 10. Q_{UN} values for a grey scale having x = y = 0.3333 in the CIE x,y chromaticity diagram with luminance levels from 0.001 cd/m^2 to 100 cd/m^2 against (a) $\log_{10}L$ and (b) stimulus size θ.

Figs. 10(a) and 10(b) show plots of the values of the Q_{UN} for a grey scale having 9 stimulus sizes across 26 luminance levels calculated using CIE illuminant D65 and the CIE 2° observer. The 26 luminance levels include 0.001 cd/m^2, 0.01 cd/m^2, 0.05 cd/m^2, 0.1 cd/m^2, 0.5 cd/m^2, 1 cd/m^2 and ranging from 5 cd/m^2 to 100 cd/m^2 in intervals of 5 cd/m^2. The 9 stimulus sizes include 0.1°, 0.3°, 0.5°, 1°, 3°, 7°, 10°, 13° and 17°. Figs. 10(a) and 10(b) also include different curves which show the trend of Q_{UN} under different stimulus size and under different luminance levels, respectively. These figures show that Q_{UN} gradually increases in value as the luminance levels are increased. In addition, the relationship between Q_{UN} and the luminance levels is gradually influenced by the stimulus size. For $0.5° < \theta \leqq 10°$, samples with larger stimulus size are brighter than those with smaller size.

Figs. 11(a) and 11(b) show the relationship between colourfulness M_{UN} and the luminance level L and the stimulus size θ. Fig. 11(a) demonstrates plots of the values of M_{UN} for green colours having 9 stimulus sizes across 26 luminance levels calculated using CIE illuminant D65 and the CIE 2° observer. The 26 luminance levels include 0.001 cd/m^2, 0.01 cd/m^2, 0.05 cd/m^2, 0.1 cd/m^2, 0.5 cd/m^2, 1 cd/m^2 and ranging from 5 cd/m^2 to 100 cd/m^2 in intervals of 5 cd/m^2. The 9 stimulus sizes include 0.1°, 0.3°, 0.5°, 1°, 3°, 7°, 10°, 13° and 17°. The CIE x, y values of these green colours were (0.2333, 0.7333). This figure shows that M_{UN} increases in value as the luminance levels are increased.

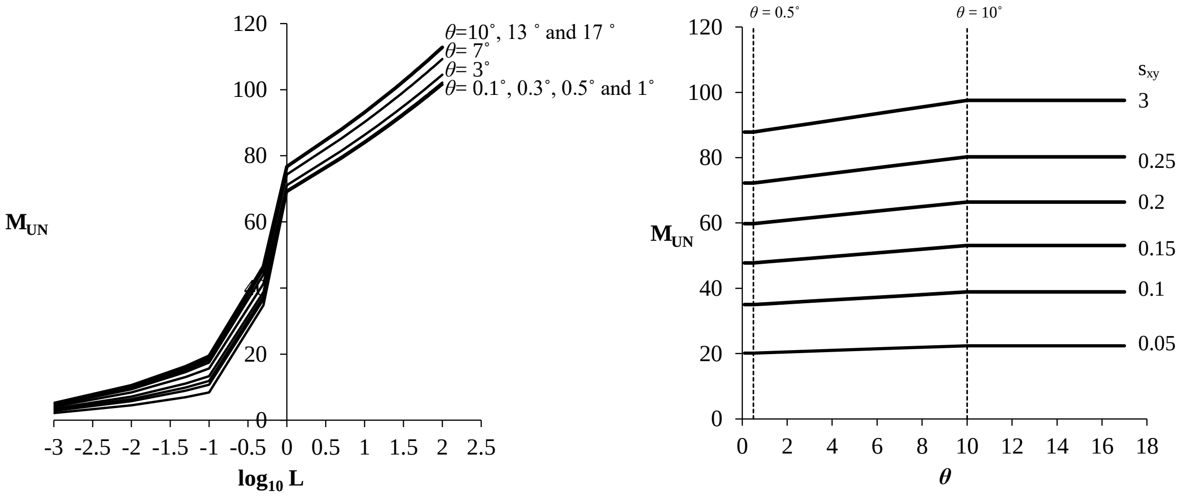


Fig. 11. (a) M_{UN} values for a set of green colours having (x, y) = (0.2333, 0.7333) in the CIE x,y chromaticity diagram with luminance levels from 0.001 cd/m^2 to 100 cd/m^2 against $\log_{10}$L. (b) M_{UN} values of the 6 green colours with saturation (s) values ranged from 0.05 to 3 at an interval of 0.05 in CIE 1931 xy chromaticity diagram against stimulus size θ.

Fig 11(b) shows the relationship between colourfulness M_{UN} and the stimulus size θ, which is demonstrated using nine stimulus sizes across six colours in the green region but different 'saturation' (s_{xy}) values (defined in equation (25)) in CIE 1931 x,y chromaticity diagram. The stimulus sizes are 0.1°, 0.3°, 0.5°, 1°, 3°, 7°, 10°, 13° and 17°.

$$s_{xy} = \sqrt{(x - 0.3333)^2 + (y - 0.3333)^2} \qquad (25)$$

where x and y are the chromaticity coordinates of a colour in CIE x,y chromaticity diagram and (0.3333, 0.3333) represents the equal energy illuminant.

The CIE x, y values of the six colours were (0.3167, 0.4000), (0.3000, 0.4667), (0.2833, 0.5333), (0.2667, 0.6000), (0.2500, 0.6667) and (0.2333, 0.7333). The s_{xy} values of these colours ranged from 0.05 to 3.00 with an interval of 0.05. They were transformed to XYZ tristimulus values in order to calculate the colourfulness M_{UN}. Each line in Fig 11 represents the relationship between M_{UN} and stimulus size θ under a defined level of s_{xy}. This figure shows that the slope of the lines gradually increases as the value of M_{UN} increases and this indicates that an increase in the stimulus size enhances the perceived colourfulness.

WORKED EXAMPLES

Table 2 presents two worked examples to verify the implementation of the comprehensive model for predicting the appearance of related colours of different stimulus sizes. Two further worked examples are given in Table 3 to verify the implementation of the model for predicting the appearance of unrelated colours. The procedure for implementing the CIECAM02 colour appearance model and its extended applications are given in Appendix.

Table 2. Worked examples for colours with different stimulus sizes

			Sample 1 (a neutral colour)			Sample 2 (a chromatic colour)		
X	Y	Z	16.6717	18.4187	21.0812	24.1916	18.4187	14.3552
X_W	Y_W	Z_W	90.52	100.00	114.46	90.52	100.00	114.46
Yb	L_A	θ	2.20	200.00	20.00	2.20	200.00	5.00
F	c	Nc	1.0	0.69	1.0	1.0	0.69	1.0
D	n	z	0.98	0.0220	1.6283	0.98	0.0220	1.6283
N_{bb}	N_{cb}	F_L	1.2489	1.2489	1.0000	1.2489	1.2489	1.0000
R	G	B	16.7061	19.6641	21.0318	23.3090	14.3321	14.4400
R_W	G_W	B_W	90.7048	106.7583	114.1915	90.7048	106.7583	114.1915
R_C	G_C	B_C	18.3839	18.4442	18.4703	25.6498	13.4430	12.6813
R_{CW}	G_{CW}	B_{CW}	99.8140	100.1353	100.2840	99.8140	100.1353	100.2840
R'	G'	B'	18.4007	18.4293	18.4712	22.4569	16.8573	12.5521
R'_W	G'_W	B'_W	99.9043	100.0570	100.2894	99.9043	100.0570	100.2894
$R'a$	$G'a$	$B'a$	7.2129	7.2175	7.2242	7.8217	6.9604	6.1733
$R'aw$	$G'aw$	$B'aw$	14.3142	14.3230	14.3364	14.3142	14.3230	14.3364
a	b	h	-0.0040	-0.0020	206.7216	0.7897	0.2706	18.9138
t	H	A	1.1056	262.3250	27.1015	146.7011	398.7158	28.2354
J	J_{size}	S_J	45.9393	55.0666	0.8312	48.1042	49.5900	0.9714

Q	Q_{size}	S_C	228.5144	250.1874	1.0786	233.8368	237.4206	1.0073
C	C_{size}		0.5519	0.5953		45.9652	46.3021	
M	M_{size}		0.5519	0.5953		45.9652	46.3021	
s	s_{size}		4.9145	4.8779		44.3362	44.1612	

Table 3. Worked examples for unrelated colours

			Sample 1 (a dark red light)			Sample 2 (a bright red light)		
X	Y	Z	0.0196	0.0100	0.0074	196.2963	100.0000	74.0741
X_W	Y_W	Z_W	100.0	100.0	100.0	100.0	100.0	100.0
Yb	θ		20.0	2.0		20.0	12.0	
F	c	Nc	0.8	0.5250	0.8	0.8	0.5250	0.8
n	z	N_{bb}	0.2	1.9272	0.9119	0.2	1.9272	0.9119
L_A	D	N_{cb}	0.0020	0.6592	0.9119	20.0	0.6867	0.9119
F_L			0.0020			0.4642		
R	G	B	174.5712	32.2958	74.7196	174.7763	32.0878	74.7933
R_W	G_W	B_W	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
R_C	G_C	B_C	174.5712	32.2958	74.7196	174.7763	32.0878	74.7933
R_{CW}	G_{CW}	B_{CW}	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000
R'	G'	B'	139.4588	76.7316	74.0000	139.5685	76.6669	74.0741
R'_W	G'_W	B'_W	100.0010	100.0000	100.0000	100.0010	100.0000	100.0000
$R'a$	$G'a$	$B'a$	1.3308	1.0583	1.0439	12.0202	9.4303	9.2995
$R'aw$	$G'aw$	$B'aw$	1.1708	1.1708	1.1708	10.5032	10.5032	10.5032
a	b	h	0.2712	0.0335	7.0396	2.5780	0.3168	7.0063
t	k_A	k_M	180.1352	23.0823	0.3001	191.2137	38.5000	1.0000
J	J_{UN}	H	106.2374	50.2294	386.8259	106.0634	385.5171	386.7938
Q	Q_{UN}	A	11.5227	7.9231	3.1617	213.3016	406.6617	30.6673
C	C_{UN}	As	98.8795	29.6740	0.2036	104.2506	104.2506	9.7437
M	M_{UN}	A_{UN}	20.7912	6.2395	7.8607	86.0489	86.0489	405.8012
s	s_{UN}		134.3269	88.7418		63.5149	45.9998	

CONCLUSION

This paper describes a comprehensive colour appearance model based on CIECAM02. The original model has been extended to predict colour appearance for visual fields of varying stimulus size and as viewed under mesopic to photopic levels of illumination. New lightness and colourfulness formulae for modelling the size effect have been developed based on the original experimental data. In addition, hypothetical data including saturation samples defined in the x, y chromaticity diagram and grey scale samples from low to high luminance levels were used to illustrate the size effect as applied to the colourfulness and brightness of stimuli. The forward model is given in an Appendix. Worked examples are also provided to aid implementation of the model. The formulation of the reverse model is complex and the subject of current work in progress.

REFERENCES

1. CIE Publication 159:2004. A Colour Appearance Model for Colour Management Systems: CIECAM02. Vienna, Austria: CIE Central Bureau; 2004.
2. CIE Publication 131:1998. The CIE 1997 Interim Colour Appearance Model (Simple Version). Vienna, Austria: CIE Central Bureau; 1998.
3. CIE Publication No. x010-1996. Proceeding of the CIE Expert Symposium'96 Colour Standards for Imaging Technology, Central Bureau, Vienna, Austria.
4. Fu CY, Li CJ, Cui GH, Luo MR, Hunt RWG, Pointer MR, An investigation of colour appearance for unrelated colours under photopic and mesopic vision, Color Res Appl 2012;37:238-254.
5. CIE Publication 170:2006. Fundamental Chromaticity Diagram with Physiological Axes - Part 1.Vienna, Austria: CIE Central Bureau.
6. Xiao K, Luo MR, Li CJ, Hong G. Colour appearance of room colours. Color Res Appl 2010;35:284-293.
7. Xiao K, Luo MR, Li CJ, Cui GH, Park D. Investigation of colour size effect for colour appearance assessment. Color Res Appl 2011;36:201-209.
8. Xiao K, Luo MR, Li CJ, Colour size effect modelling. Color Res Appl 2012;37:4-12.
9. CIE Publication 17.4 1987. International Lighting Vocabulary, 4th edition. Vienna, Austria: CIE Central Bureau 1987.
10. Luo MR, Cui GH, Li CJ, Rigg B. Uniform colour spaces based on CIECAM02 colour appearance model. Color Res Appl 2006;31:320-330.
11. Luo MR, Cui GH, Rigg B., The development of the CIE 2000 colour-difference formula: CIEDE2000, Color Res Appl 2001;26:340-350.
12. ISO 11664-6:2012/CIE S 014-6/E:2012: Joint ISO/CIE Standard: Colorimetry — Part 6: CIEDE2000 colour-difference formula. Vienna, Austria: CIE Central Bureau; 2012.
13. Luo MR, Rigg B. BFD(l:c) colour-difference formula. Part I – Development of the fomula, J. Soc., Dyers Colour. 1986:11:86-94.
14. Kim DH, Nobbs J. New weighting functions for weighted CIELAB color difference formula, In proceedings of AIC Colour 97 (AIC 1997). Vol. 1 446-449.
15. Berns R. Alman DH, Reniff L., Snyder GD, Balonon-Rosen MR, Visual determination of supra-threshold color-difference tolerances using probit analysis, Color Res Appl 1991;16:297-316.
16. Witt K., Geometric relations between scales of small color differences, Color Res Appl 1999;24:78-92.
17. Choi SY, Luo MR, Pointer MR, Li CJ, Rhodes PA. Changes in colour appearance of a large display in various surround ambient conditions. Color Res Appl 2010;35:200-212.
18. Park YK, Luo MR, Li CJ, Kwak YS. Refined CIECAM02 for bright surround conditions. Color Res Appl 2015;40:114-125.
19. Luo MR, Clarke AA, Rhodes PA, Schappo A, Scrivener SAR, Tait TJ, Quantifying colour appearance: Part I – LUTCHI colour appearance data. Color Res Appl 1991;16:166-180.

20. Luo MR, Clarke AA, Rhodes PA, Schappo A, Scrivener SAR, Tait TJ. Quantifying colour appearance: Part II – Testing colour models' performance using LUTCHI colour appearance data. Color Res Appl 1991;16: 181-197.

Appendix. The Comprehensive Colour Appearance Model

Input

1. X, Y, Z: (under test illuminant X_W, Y_W, Z_W).
2. θ: size of the test stimulus.

Output

1. Lightness J, chroma C, hue composition H, hue angle h, colourfulness M, saturation s, and brightness Q of a related colour with the viewing size of 2° for the original CIECAM02 model.
2. J_{Size}, C_{Size} and hue composition H, or colourfulness M_{Size}, saturation s_{Size} and brightness Q_{Size} for the size-effect.
3. J_{UCS}, M_{UCS} and H or h for a related colour in CAM02-UCS uniform colour space
4. Brightness Q_{UN}, colourfulness M_{UN} and hue composition H for unrelated colours

---

Illuminants, viewing surrounds and background parameters

Adopted white in test illuminant: X_w , Y_w , Z_w

Background in test conditions: Y_b

(Reference white in reference illuminant: $X_{wr} = Y_{wr} = Z_{wr} = 100$, which are fixed in the model)

Luminance of test adapting field (cd/m^2) : L_A

All surround parameters are given in Table A1 below

Table A1. Surround Parameters

	F	c	N_C
Average	1.0	0.69	1.0
Dim	0.9	0.59	0.9
Dark	0.8	0.525	0.8

N_C and F are modelled as a function of c, and can be linearly interpolated as shown in the Fig.A1 below, using the above points

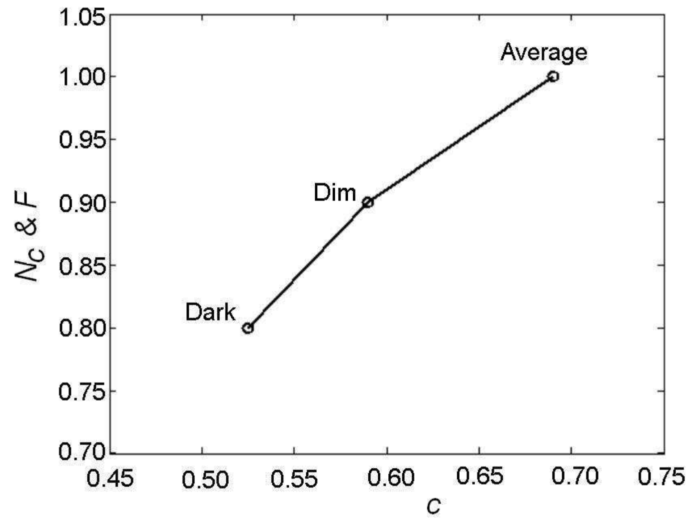


Fig.A1 N_c and F varies with c.

For unrelated colours, the adopted white is set as the equal energy illuminant (S_E) having tristimulus values of $X_W = Y_W = Z_W = 100$. In the application, there is no reference white for unrelated colours. The luminance factor of the surround Y_b should set to 20. The luminance of the adapting field L_A is taken as 1/5 of the luminance level of the target stimulus Y. The surround parameters are set as those under the dark viewing condition in Table A1.

Step 0: Calculate all values/parameters which are independent of input samples

$$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix} = M_{CAT02} \cdot \begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix}, \; D = F \cdot [\, 1 - \left(\frac{1}{3.6}\right) \cdot e^{\left(\frac{-L_A - 42}{92}\right)} \,]$$

Note if D is greater than one or less than zero, set it to one or zero respectively.

$$D_R = D \cdot \frac{Y_w}{R_w} + 1 - D, \quad D_G = D \cdot \frac{Y_w}{G_w} + 1 - D, \quad D_B = D \cdot \frac{Y_w}{B_w} + 1 - D,$$

$$F_L = 0.2\, k^4 \cdot (5L_A) + 0.1\, (1-k^4)^2 \cdot (5\, L_A)^{1/3},$$

where $$k = \frac{1}{5 \cdot L_A + 1}.$$

$$n = \frac{Y_b}{Y_W}, \quad z = 1.48 + \sqrt{n}\,, \quad N_{bb} = N_{cb} = 0.725 \cdot \left(\frac{1}{n}\right)^{0.1425}$$

$$\begin{pmatrix} R_{wc} \\ G_{wc} \\ B_{wc} \end{pmatrix} = \begin{pmatrix} D_R \cdot R_w \\ D_G \cdot G_w \\ D_B \cdot B_w \end{pmatrix}, \; \begin{pmatrix} R'_w \\ G'_w \\ B'_w \end{pmatrix} = M_{HPE} \cdot M_{CAT02}^{-1} \cdot \begin{pmatrix} R_{wc} \\ G_{wc} \\ B_{wc} \end{pmatrix}$$

$$M_{CAT02} = \begin{pmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{pmatrix}$$

$$M_{HPE} = \begin{pmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{pmatrix}$$

$$R'_{aw} = 400 \cdot \left(\frac{(\frac{F_L \cdot R'_w}{100})^{0.42}}{(\frac{F_L \cdot R'_w}{100})^{0.42} + 27.13} \right) + 0.1$$

$$G'_{aw} = 400 \cdot \left(\frac{(\frac{F_L \cdot G'_w}{100})^{0.42}}{(\frac{F_L \cdot G'_w}{100})^{0.42} + 27.13} \right) + 0.1$$

$$B'_{aw} = 400 \cdot \left(\frac{(\frac{F_L \cdot B'_w}{100})^{0.42}}{(\frac{F_L \cdot B'_w}{100})^{0.42} + 27.13} \right) + 0.1$$

$$A_w = [2 \cdot R'_{aw} + G'_{aw} + \frac{B'_{aw}}{20} - 0.305] \cdot N_{bb}$$

Note that all parameters computed in this step are needed for the following calculations. However, they depend only on the surround and the viewing conditions, hence when processing the pixels of an image they are computed only once. The following computing steps are sample dependant.

Step 1: For unrelated colours, normalise X, Y, Z, such that the luminance level of the target stimulus is equal to 100.

$X' = X \cdot 100 / Y$

$Y' = 100$

$Z' = Z \cdot 100 / Y$

Step 2: Calculate (sharpened) cone responses (transfer colour matching functions to sharper sensors)

$$\begin{bmatrix} \boldsymbol{R} \\ \boldsymbol{G} \\ \boldsymbol{B} \end{bmatrix} = \boldsymbol{M}_{\mathbf{CAT02}} \cdot \begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \\ \boldsymbol{Z} \end{bmatrix} \quad \text{for related colours}$$

$$\begin{bmatrix} \boldsymbol{R} \\ \boldsymbol{G} \\ \boldsymbol{B} \end{bmatrix} = \boldsymbol{M}_{\mathbf{CAT02}} \cdot \begin{bmatrix} \boldsymbol{X'} \\ \boldsymbol{Y'} \\ \boldsymbol{Z'} \end{bmatrix} \text{ for unrelated colours}$$

Step 3: Calculate the corresponding (sharpened) cone response (considering various luminance level and surround conditions included in D, hence in D_R, D_G, and D_B)

$$\begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} = \begin{pmatrix} D_R \cdot R \\ D_G \cdot G \\ D_B \cdot B \end{pmatrix},$$

Step 4: Calculate the Hunt-Pointer-Estevez response

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{HPE} \cdot M_{CAT02}^{-1} \cdot \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix},$$

Step 5: Calculate the post-adaptation cone response (resulting in dynamic range compression)

$$R_a' = 400 \cdot \left(\frac{(\frac{F_L \cdot R'}{100})^{0.42}}{(\frac{F_L \cdot R'}{100})^{0.42} + 27.13} \right) + 0.1$$

If R' is negative, then

$$R_a' = -400 \cdot \left(\frac{(\frac{-F_L \cdot R'}{100})^{0.42}}{(\frac{-F_L \cdot R'}{100})^{0.42} + 27.13} \right) + 0.1$$

and similarly for the computations of G_a', and B_a' respectively.

Step 6: Calculate Redness – Greenness (a), Yellowness – Blueness (b) components, and hue angle (h):

$$a = R_a' - \frac{12 \cdot G_a'}{11} + \frac{B_a'}{11}$$

$$b = \frac{(R_a' + G_a' - 2 \cdot B_a')}{9}$$

$$h = \tan^{-1}(\frac{b}{a})$$

making sure h is between 0° and 360°.

Step 7: Calculate eccentricity (e_t) and hue composition (H), using the unique hue data given in Table A2; set $h' = h + 360$ if $h < h_1$, otherwise $h' = h$. Choose a proper i (i =1, 2, 3 or 4) so that $h_i \le h' < h_{i+1}$. Calculate

$$e_t = \frac{1}{4} \cdot \left[\cos\left(\frac{h' \cdot \pi}{180} + 2 \right) + 3.8 \right]$$

which is close to, but not exactly the same as, the eccentricity factor given in Table A2.

Table A2. Unique hue data for calculation of hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0.0	100.0	200.0	300.0	400.0

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

Note that the hue composition H is identical for both related colours and unrelated colours.

Step 8: Calculate achromatic response A

$$A = [2 \cdot R'_a + G'_a + \frac{B'_a}{20} - 0.305] \cdot N_{bb}$$

Step 9: Calculate the correlate of lightness (J, J_{Size} or J_{UN})

$$J = 100 \cdot \left(\frac{A}{A_w}\right)^{c \cdot z}$$

For considering size-effect,

$$J_{\mathrm{Size}} = 100 + SJ \cdot (J - 100)$$

where $SJ = {}_J \times r^2 + {}_J \times r + (1 \quad {}_J \quad {}_J)$

$r = \frac{\theta}{\theta_M}$ for $\theta \geqq \theta_M$

r = 1 for $\theta < \theta_M$

θ_M represents the CIE standard observer adopted when measuring the colour stimuli, i.e. either 2° or 10°. Default value is 2°.

α_J = 0.0000437; β_J = -0.01924;

For unrelated colours,

$$J_{UN} = 6.25 \cdot \left[\frac{c \cdot Q_{UN}}{(A_W + 4) \cdot F_L^{0.25}}\right]^2$$

Note that for the calculation of Q_{UN}, see Step 10.

Step 10: Calculate the correlate of brightness (Q, Q_{Size} and Q_{UN})

$$Q = \left(\frac{4}{c}\right) \cdot \left(\frac{J}{100}\right)^{0.5} \cdot (A_w + 4) \cdot F_L^{0.25}$$

For considering size-effect,

$$Q_{Size} = \left(\frac{4}{c}\right) \cdot \left(\frac{J_{Size}}{100}\right)^{0.5} \cdot (A_W + 4) \cdot F_L^{0.25}$$

For unrelated colours,

$Q_{UN} = A_{UN} + M_{UN}/100$

where

$A_{UN} = A + K_A \cdot A_s$

$A_S = L_S^{0.42}$

$L_S = 2.26 \cdot Y$

In the cases of $Y \geqq 1 cd/m^2$,

$K_A = -5.3 \cdot \log_{10}(Y) + 44.5$ for $\theta \leq 0.5°$

$K_A = (0.0119 \cdot \theta + 0.994) \cdot (-5.3 \cdot \log_{10}(Y) + 44.5) + 0.0801 \cdot \theta - 0.039$

for $10° \geq \theta > 0.5°$

$K_A = -5.9 \cdot \log_{10}(Y) + 50.3$ for $\theta > 10°$

In the cases of $1 > Y \geqq 0.1 cd/m^2$

$K_A = 1.41 (1-L) \log_{10}\theta + 30.67L + 19.63$ for $\theta \geqq 10°$

$K_A = 1.41\,(1–L)\,\log_{10}\theta + 0.679\,(L–0.1)\theta + 23.88L + 20.314$ for $0.5° \leqq \theta < 10°$

$K_A = 1.41\,(1–L)\,\log_{10}\theta + 24.22L + 20.28$ for $\theta < 0.5°$

In the cases where Y< 0.1cd/m^2

$K_A = 1.27 \cdot \log_{10}(\theta) + 22.7$

Note that for the calculation of M_{UN}, see Step 11.

Step 11: Calculate the correlates of chroma (C, C_{Size} or C_{UN}), colourfulness (M, M_{Size} or M_{UN}) and saturation (s, s_{Size} or s_{UN})

$$t = \frac{\left(\frac{50000}{13} \cdot N_c \cdot N_{cb}\right) \cdot e_t \cdot \left(a^2 + b^2\right)^{1/2}}{R'_a + G'_a + (\frac{21}{20}) \cdot B'_a}$$

$$C = t^{0.9} \cdot (\frac{J}{100})^{0.5} \cdot (1.64 - 0.29^n)^{0.73} \qquad M = C \cdot F_L^{0.25} \qquad s = 100 \cdot (\frac{M}{Q})^{0.5}$$

For considering size-effect,

$$C_{\text{Size}} = SC \cdot C$$

$$M_{\text{Size}} = C_{\text{Size}} \cdot F_L{}^{0.25} \qquad s_{\text{Size}} = 100 \cdot \left(\frac{M_{\text{Size}}}{Q_{\text{Size}}}\right)^{0.5}$$

where

$$SC = \alpha_C \cdot r^2 + \beta_C \cdot r + (1 - \alpha_C - \beta_C)$$

$r = \frac{\theta}{\theta_M}$ for $\theta \geqq \theta_M$

$r = 1$ for $\theta < \theta_M$

$\alpha_C = 0.000513$; $\beta_C = 0.003091$

For unrelated colours,

$$M_{UN} = K_M \cdot M \qquad C_{\text{UN}} = \frac{M_{\text{UN}}}{F_L{}^{0.25}} \qquad s_{\text{UN}} = 100 \cdot \left(\frac{M_{\text{UN}}}{Q_{\text{UN}}}\right)^{0.5}$$

In the cases of Y≧1cd/m^2

$K_M = 0.9$ for $\theta \leq 0.5°$

$K_M = 0.0105 \cdot \theta + 0.895$ for $10° \geq \theta > 0.5°$

$K_M = 1.0$ for $\theta > 10°$

In the cases of $1 > Y \geqq 0.1 cd/m^2$

$$K_M = 0.11\,(1-L)\log_{10}\theta + 0.81L + 0.19 \qquad \text{for } \theta \geqq 10°$$

$$K_M = 0.11\,(1-L)\log_{10}\theta + 0.012\,(L-0.1)\theta + 0.694L + 0.201 \qquad \text{for } 0.5° \leqq \theta < 10°$$

$$K_M = 0.11\,(1-L)\log_{10}\theta + 0.7L + 0.2 \qquad \text{for } \theta < 0.5°$$

In the cases of $Y < 0.1 cd/m^2$

$$K_M = 0.1 \cdot \log_{10}(\theta) + 0.27$$

Step 12: For CAM02-UCS, the following equations are used.

$$J_{\mathrm{UCS}} = \frac{1.7 \cdot J}{1 + 0.007 \cdot J}$$

$$M_{\mathrm{UCS}} = \frac{\ln(1 + 0.0228 \cdot M)}{0.0228}$$

$$\begin{cases} a_{\mathrm{UCS}} = M_{\mathrm{UCS}} \cdot \cos(h) \\ b_{\mathrm{UCS}} = M_{\mathrm{UCS}} \cdot \sin(h) \end{cases}$$