

The CIECAM02 Color Appearance Model

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Abstract

The CIE Technical Committee 8-01, color appearance models for color management applications, has recently proposed a single set of revisions to the CIECAM97s color appearance model. This new model, called CIECAM02, is based on CIECAM97s but includes many revisions¹⁻⁴ and some simplifications. A partial list of revisions includes a linear chromatic adaptation transform, a new non-linear response compression function and modifications to the calculations for the perceptual attribute correlates. The format of this paper is an annotated description of the forward equations for the model.

Introduction

The CIECAM02 color appearance model builds upon the basic structure and form of the CIECAM97s^{5,6} color appearance model. This document describes the single set of revisions to the CIECAM97s model that make up the CIECAM02 color appearance model. There were many, often conflicting, considerations such as compatibility with CIECAM97s, prediction performance, computational complexity, invertibility and other factors.

The format for this paper will differ from previous papers introducing a color appearance model. Often a general description of the model is provided, then discussion about its performance and finally the forward and inverse equations are listed separately in an appendix. Performance of the CIECAM02 model will be described elsewhere⁷ and for the purposes of brevity this paper will focus on the forward model. Specifically, this paper will attempt to document the decisions that went into the design of CIECAM02. For a complete description of the forward and inverse equations, as well as usage guidelines, interested readers are urged to refer to the TC 8-01 web site⁸ or to the CIE for the latest draft or final copy of the technical report. This paper is not intended to provide a definitive reference for implementing CIECAM02 but as an introduction to the model and a summary of its structure.

Data Sets

The CIECAM02 model, like CIECAM97s, is based primarily on a set corresponding colors experiments and a collection of color appearance experiments. The corresponding color data sets^{9,10} were used for the optimization of the chromatic adaptation transform and the D factor. The LUTCHI color appearance data^{11,12} was the basis for optimization of the perceptual attribute correlates. Other data sets and spaces were also considered. The NCS system was a reference for the e and hue fitting. The chroma scaling was also compared to the Munsell Book of Color. Finally, the saturation equation was based heavily on recent experimental data.¹³

Summary of Forward Model

A color appearance model^{14,15} provides a viewing condition specific means for transforming tristimulus values to or from perceptual attribute correlates. The two major pieces of this model are a chromatic adaptation transform and equations for computing correlates of perceptual attributes, such as brightness, lightness, chroma, saturation, colorfulness and hue. The chromatic adaptation transform takes into account changes in the chromaticity of the adopted white point. In addition, the luminance of the adopted white point can influence the degree to which an observer adapts to that white point. The degree of adaptation or D factor is therefore another aspect of the chromatic adaptation transform. Generally, between the chromatic adaptation transform and computing perceptual attributes correlates there is also a non-linear response compression. The chromatic adaptation transform and D factor was derived based on experimental data from corresponding colors data sets. The non-linear response compression was derived based on physiological data and other considerations. The perceptual attribute correlates was derived by comparing predictions to magnitude estimation experiments, such as various phases of the LUTCHI data, and other data sets, such as the Munsell Book of Color.

Finally the entire structure of the model is generally constrained to be invertible in closed form and to take into account a sub-set of color appearance phenomena.

Viewing Condition Parameters

It is convenient to begin by computing viewing condition dependent constants. First the surround is selected and then values for F, c and Nc can be read from Table 1. For intermediate surrounds these values can be linearly interpolated.²

Table. 1. Viewing condition parameters for different surrounds.

Surround	F	c	Nc
Average	1.0	0.69	1.0
Dim	0.9	0.59	0.95
Dark	0.8	0.525	0.8

The value of F_L can be computed using equations 1 and 2, where L_A is the luminance of the adapting field in cd/m^2 . Note that this two piece formula quickly goes to very small values for mesopic and scotopic levels and while it may resemble a cube-root function there are considerable differences between this two-piece function and a cube-root as the luminance of the adapting field gets very small.

$$k = 1 / (5L_A + 1) \quad (1)$$

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

The value n is a function of the luminance factor of the background and provides a very limited model of spatial color appearance. The value of n ranges from 0 for a background luminance factor of zero to 1 for a background luminance factor equal to the luminance factor of the adopted white point. The n value can then be used to compute N_{bb} , N_{cb} and z, which are then used during the computation of several of the perceptual attribute correlates. These calculations can be performed once for a given viewing condition.

$$n = Y_b / Y_w \quad (3)$$

$$N_{bb} = N_{cb} = 0.725(1/n)^{0.2} \quad (4)$$

$$z = 1.48 + \sqrt{n} \quad (5)$$

Chromatic Adaptation

Once the viewing condition parameters have been computed, input tristimulus values can be processed. The processing begins with the chromatic adaptation transform. This transform consists of three major components. First, is the space in which the transform is applied. Second, is the

specific transform and third is a model of incomplete adaptation.

There were 8 different data sets^{9,10} considered for the optimization of the space for the chromatic adaptation transform. The data sets selected for use were those whose viewing conditions most resembled viewing conditions for typical imaging applications. A plot of all the white points for all the data sets is shown in Figure 1. Only the McCann et al. data set¹⁶ was not included for the final optimization. This data set was derived using highly chromatic, low levels of illumination. While this data has potential implications for our understanding of color perception there was lack of agreement on its utility to TC8-01.

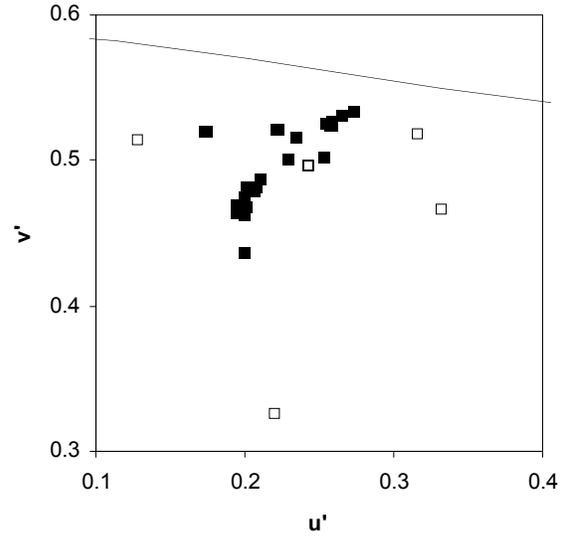


Fig. 1. The filled squares show white points for the data sets used to derive CAT02. Open squares show data considered but not used.

The space selected for use for the CIECAM02 model was the modified Li et al. RGB space, also known as the modified CMCCAT2000 transform. For the remainder of this paper it will be referred to as CAT02. The selection of CAT02 from the multiple candidates^{2,17-21} was among the most difficult issues addressed by the committee and the final transform was not the first choice of any of the authors. Means testing of prediction errors, error propagation analysis and psychophysical evaluation showed little or no significant differences between the six candidate transforms considered by the committee. However, CAT02 has similar performance to the non-linear Bradford transform of CIECAM97s and is therefore reasonably backwards compatible with CIECAM97s. In addition, runs-testing of the residual prediction errors shows some trends favoring CAT02. The equal-energy balanced matrix for converting tristimulus values to the CAT02 space can be written:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (6)$$

$$\mathbf{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad (7)$$

The D factor or degree of adaptation is a function of the surround and L_A and in theory could range from 0 for no adaptation to the adopted white point to 1 for complete adaptation to the adopted white point. In practice the minimum D value will not be less than 0.65 for a dark surround and will exponentially converge to 1 for average surrounds with increasingly large values of L_A . A graph of D versus L_A for three surrounds is shown in Figure 2. The formula for D is:

$$D = F \left[1 - \left(\frac{1}{3.6} \right) e^{\left(\frac{-L_A - 42}{92} \right)} \right] \quad (8)$$

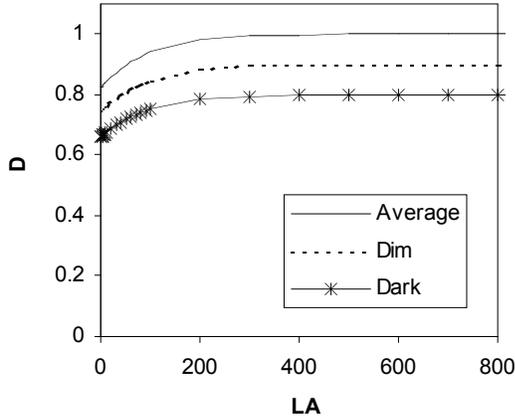


Fig. 2. Degree of adaptation computed using L_A and surround.

Given the D factor and data transformed using \mathbf{M}_{CAT02} , the full chromatic adaptation transform can be written:

$$R_c = \left[\left(Y_w \frac{D}{R_w} \right) + (1 - D) \right] R \quad (9)$$

Where the w subscript denotes the corresponding value for the white point and the c subscript denotes stimulus values. G_c and B_c can be calculated in a similar manner, as can R_{cw} , G_{cw} and B_{cw} . Equation 9 includes the factor Y_w in the calculation so that the adaptation is independent of the

luminance factor of the adopted white point. For example a reflection print could have a Y_w of less than 100, say equal to 90. Such a print under an equi-energy illuminant would have values of X_w , Y_w , Z_w and R_w , G_w , B_w all equal to 90. In this case R_c , G_c , B_c will be equal to $(D/9 + 1)R$, $(D/9 + 1)G$, $(D/9 + 1)B$; but, because the equi-energy illuminant is being used, there is no chromatic adaptation, and R_c , G_c , B_c should be equal to R , G , B . Multiplication by Y_w ensures that the adaptation is independent of the luminance factor of the adopted white point.

The R_c , G_c and B_c values are then converted to Hunt-Pointer-Estevéz space²² before the post-adaptation non-linear response compression is applied. CIECAM02, like CIECAM97s, makes use of one space for the chromatic adaptation transform and another for computing perceptual attribute correlates. This adds complexity to the model but pending additional research, it would appear that chromatic adaptation results are best predicted in a space that has some degree of sharpening. The nature and degree of this sharpening is still subject to debate but it should be noted that CAT02 does incorporate some degree of sharpening. In comparison the use of a space closer to the cone fundamentals, such as the Hunt-Pointer-Estevéz or Stockman-Sharpe fundamentals, provides better predictions of perceptual attribute correlates. Blue constancy, a significant shortcoming for CIELAB, is considerably improved by using a space closer to a cone fundamental space.²³

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathbf{M}_H \mathbf{M}_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \quad (10)$$

$$\mathbf{M}_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix} \quad (11)$$

$$\mathbf{M}_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix} \quad (12)$$

Non-Linear Response Compression

The post-adaptation non-linear response compression is then applied to the output from equation 10. CIECAM97s used a hyperbolic function but some shortcomings were noticed with this function. A number of other functions were considered but ultimately a modified hyperbolic function was selected. This function is based on a generalized Michaelis-Menten equation²⁴ and is consistent with Valetton and van Norren's²⁵ physiologically derived data. The specifics of this function and its advantages will be discussed elsewhere.⁴ A log-log plot of the compression

function for L_a of 200 (for which F_L is equal to 1) is shown in Figure 3.

The CIECAM02 non-linearity converges to a finite value for increasingly large intensities and has a gradual toe for increasingly small intensities. If any of the values of R' , G' , or B' are negative, then their positive equivalents must be used, and then R'_a , G'_a , and B'_a must be made negative. Equation 13 shows the specific equation for the non-linearity and values for G'_a and B'_a can be calculated in a similar manner, as can R'_{aw} , G'_{aw} and B'_{aw} .

$$R'_a = \left[\frac{400(F_L R'/100)^{0.42}}{27.13 + (F_L R'/100)^{0.42}} \right] + 0.1 \quad (13)$$

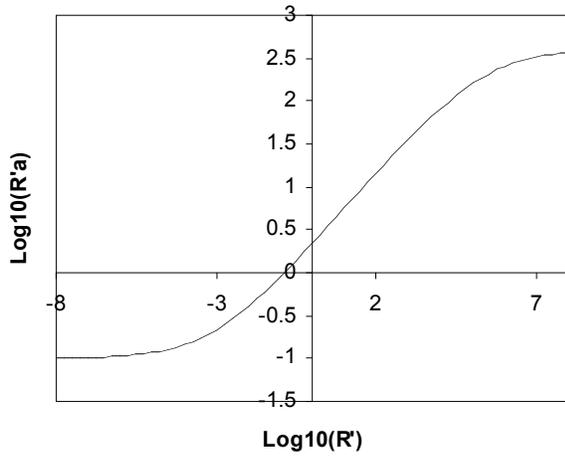


Fig. 3. Log-log plot of CIECAM02 non-linearity.

Perceptual Attribute Correlates

Preliminary Cartesian coordinates, a and b , are computed from the output from equation 13. These values are used, in turn, to compute a preliminary magnitude t and should not be confused with the final Cartesian coordinates shown in Equations 24 and 25.

$$a = R'_a - 12G'_a / 11 + B'_a / 11 \quad (14)$$

$$b = (1/9)(R'_a + G'_a - 2B'_a) \quad (15)$$

$$t = \frac{e^{(a^2 + b^2)^2}}{R'_a + G'_a + (21/20)B'_a} \quad (16)$$

A hue angle, h , is computed and this angle is also used to compute an eccentricity factor. This eccentricity value ranges from 0.8 to 1.2 as a function of the value of h . To compute hue composition or H equation 19 is used. For the unique hues, red, yellow, green, and blue, values for h are

20.14, 90, 164.25, 237.53 and 380.14. The corresponding values for e are 0.8, 0.7, 1.0, 1.2 and 0.8. Finally, the corresponding values for H_i are 0, 100, 200, 300 and 400.

$$h = \tan^{-1}(b/a) \quad (17)$$

$$e = \left(\frac{12500}{13} N_c N_{cb} \right) \left[\cos \left(h \frac{\pi}{180} + 2 \right) + 3.8 \right] \quad (18)$$

$$H = H_i + \frac{100(h - h_1)/e_1}{(h - h_1)/e_1 + (h_2 - h)/e_2} \quad (19)$$

The achromatic response or A can then be computed, as can be seen in equation 20. The noise term determines the minimum lightness value and, for the CIECAM02 model it is set to of -0.305 so that A will be zero when Y is zero. The value for lightness or J is computed using the same equation as for CIECAM97s but note that other modifications in the calculations mean that computed value for J is not identical to CIECAM97s even though the equations are identical. Also note that A_w in equation 21 is the achromatic response for the white point. This means that the calculations shown in equations 6 through 20 must be performed once for each viewing condition or adopted white point. For compactness, this is not shown but when they are shown the important notation of a trailing lower case w in the subscript must be used. Given the achromatic response and lightness, the perceptual attribute correlate for brightness or Q can then be computed.

$$A = [2R'_a + G'_a + (1/20)B'_a - 0.305] N_{bb} \quad (20)$$

$$J = 100(A/A_w)^{cz} \quad (21)$$

$$Q = (4/c) \sqrt{J/100} (A_w + 4) F_L^{0.25} \quad (22)$$

Given lightness and the temporary magnitude, t , the value for chroma can then be computed as shown in equation 23. This new equation in combination with the revised non-linear response compression reduces the intercept term²⁶ for chroma fit. The value for colorfulness or M can then be computed from the chroma correlate. Finally the value for the saturation correlate or s can be calculated. Note that the form for the saturation²⁷ correlate is considerably different than that used in CIECAM97s.

$$C = t^{0.9} \sqrt{J/100} (.64 - 0.29^n)^{.73} \quad (23)$$

$$M = CF_L^{0.25} \quad (24)$$

$$s = 100 \sqrt{M/Q} \quad (25)$$

Finally, given C , M or s and h a Cartesian representation can be computed. This is shown in equations 26 and 27 using the chroma correlate. The subscript C is used to specify the use of the chroma correlate and corresponding equations exist for a_M , b_M , a_s and b_s . The subscripts should be used to avoid confusion both with the preliminary Cartesian coordinates shown in equations 14 and 15 and to specify which perceptual attribute correlate is the coordinates are based on.

$$a_C = C \cos(h) \quad (26)$$

$$b_C = C \sin(h) \quad (27)$$

Conclusion

The CIECAM02 model has been described and its forward equations presented. This model is based on the CIECAM97s model and incorporates a number of revisions and simplifications. These include a linear chromatic adaptation transform based on the modified Li et al. matrix, a different hyperbolic post adaptation non-linear response compression function and changes to the perceptual attribute correlates. This model has attempted to balance backwards compatibility with CIECAM97s, prediction accuracy for a range of data sets, complexity, current understanding of certain aspects of the human visual system, and invertibility.

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Biography

The authors of this paper have a combined 125 plus years experience in color science. They include chairs of TC1-3 that prepared CIE publication 15.2, TC1-34 that developed the CIECAM97s model and TC1-52 that overviewed the development of chromatic adaptation transforms. The authors span eight time zones, two academic institutions and two corporations.

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Keywords

Color Appearance Models, CIECAM97s, Chromatic Adaptation Transforms, Perceptual Attribute Correlates