Color Reproduction and Color Vision Modeling

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Abstract

The principles of spectral color reproduction, as exemplified by the Lippmann method, and of trichromatic color reproduction, as used by presentday systems, are reviewed. Colorimetry is also based on trichromatic principles, and provides the basis for the quantitative evaluation of color reproduction in television, photography, and printing. Being metameric, these reproductions are affected by changes in illuminant and observer. They are also sensitive to changes in their viewing conditions; these changes can be represented by color vision models, one of which is briefly described.

Spectral Color Reproduction

Colors are defined physically by their spectral power distributions. To reproduce colors with the same spectral power distributions as in the original scene is difficult. The most elegant method so far devised for doing this is the interference method invented by Lippmann. However, its low sensitivity and general inconvenience have made it obsolete for many years.

Trichromatic Color Reproduction

Because the eye does not respond to each wavelength of the spectrum, but only to the light in three broad bands, it is possible to reproduce colors *trichromatically,* by displaying them as mixtures of red, green, and blue light.

Colorimetry

Colorimetry also depends on the trichromatic principle. Colors of each wavelength of the spectrum were matched with mixtures of red, green, and blue light by groups of observers, and the results averaged to represent the response of *Standard Colorimetric Observers.* These data have led to the now universally-used CIE system of colorimetry, with its X,Y,Z tristimulus values, the x,y and u',v', chromaticity diagrams, and the CIELUV and CIELAB color spaces.

Television

If a television camera has the same spectral sensitivity functions as those of the three different types of cone in the eye, correct color reproduction does not occur because each display color stimulates more than one of the three different cone types. This is true whether the display device uses a cathode-ray tube, a triple projector, or a liquid crystal array. These *unwanted stimulations* result in the colors in the reproduction having reduced saturation and distorted hues. These errors can be corrected by passing the signals from the camera through a matrixing circuit which removes the effects of the unwanted stimulations; but this can only succeed within the gamut of reproducible colors. Colors outside this gamut require negative signals which cannot be displayed. The gamut limitation cannot be avoided, because it results from the overlapping nature of the cone spectral sensitivities.

Photography

In photography, the display normally consists of cyan, magenta, and yellow dye images, and the bands of wavelengths controlled by them also result in unwanted stimulations. But, unlike television, photography can provide no convenient way of introducing matrixing. What is usually done is to increase the wavelength separation of the three spectral sensitivities of the film as compared to those of the eye, and this improves the fidelity of most colors, although it introduces marked hue errors for a few colors such as certain types of blue flower. The dyes used in photography also absorb in parts of the spectrum where they should not do so, and these *unwanted absorptions* result in colors being too dark; however, the use of colored couplers and inter-image effects are very effective in making the necessary corrections.

Half-tone and Digital Printing

In conventional printing, the modulation of the light in the display by the cyan, magenta, and yellow inks is achieved by varying the size of dots of ink that are small enough not to be resolved by the eye at normal viewing distances. In digital printing, it is necessary to construct these *half-tone* dots from patterns of *micro-dots;* to avoid spurious contouring effects, about ten times as many micro-dots are required per unit distance as compared to the number of half-tone dots. For high quality work this requires microdots of about 1/100 mm in diameter. However, by distributing the micro-dots in *dithered* patterns instead of in clusters, or by using *error diffusion* techniques (distribution over neighbouring pixels of the errors caused by using too few micro-dots) high quality results can be obtained with larger micro-dots.

Metamerism

Trichromatic reproductions inevitably result in almost all colors being reproduced with spectral power distributions that are markedly different from those in the original scene. This *metamerism* means that even if the reproduction matches the original for one illuminant and observer, it will not necessarily do so for others. Non-self-luminous displays, such as liquid crystal television devices, photographic transparencies and reflection prints, printed papers, and desktop publications, are therefore sensitive to changes in the spectral power distribution of their illuminant; and all displays, including self-luminous devices such as cathode-ray tubes, are sensitive to changes in observer, such as may arise because an individual observer differs significantly from a chosen CIE Standard Observer.

Evaluation of Color Differences

The colorimetric evaluation of color differences in color reproduction is usually carried out using the CIE 1931 Standard Colorimetric Observer; the data on which this observer is based were obtained with fields of 2° angular subtense, whereas those for the CIE 1964 Observer were obtained with fields of 10° subtense, which are much larger than typical uniform areas in pictures. The CIE color difference formulae associated with the CIELUV and CIELAB color spaces are widely used, the former usually for self-luminous displays, and the latter usually for non-self-luminous displays. These formulae are appropriate if the original and reproduction are viewed under the same conditions, and the white points are not too different from those that occur in typical daylight. For other illuminants, and for asymmetrical viewing situations, more elaborate procedures are necessary, and a model of color vision may be used.

A Model of Color Vision

The conditions under which colors are viewed affect their appearance. Because of this, it is not appropriate, for instance, to represent colors on reflection copy by displaying the same tristimulus values on a cathode-ray tube. It is necessary to determine the appearance of the colors in the reflection copy and then to display on the cathode-ray tube colors having those tristimulus values that result in the same appearance. A model of color vision can be used to determine these appearances. Details of the steps required to use one such model are given below. This model, referred to originally as the Hunt 91 model[1], has now been provided with improved predictors of chroma and colorfulness[2]; these are incorporated in this paper, and this constitutes the version identified as the Hunt 94 model.

Main Features of the Model

For the spectral sensitivities of the cones of the retina, the model uses a linear combination of the CIE $\bar{x}$, $\bar{y}$, and $\bar{z}$ color matching functions; this means that the input to the model can be in the form of CIE tristimulus values, X, Y, and Z. The way in which the cones respond to variations in stimulus intensity is represented by a function that has a gradual transition to a minimum at very low intensities, and a gradual transition to a maximum at very high intensities. Adaptation is allowed for by first dividing the cone responses by those for a suitably chosen reference white, and then reducing the effect of this division by means of a luminance-level adaptation factor, three chromatic adaptation factors, three cone bleach factors, and three Helson-Judd effect factors. The resulting modified cone responses, ρ_a, γ_a, and β_a, are used to form three color difference signals:

$$C_1 = \rho_a - \gamma_a\,;\;\; C_2 = \gamma_a - \beta_a\,;\; C_3 = \beta_a - \rho_a\,.$$

An achromatic signal, A, is also formed by combining the three responses, ρ_a, γ_a, and β_a, in proportions that allow for the different abundances of the three types of cone, together with a response, A_S, from the rods of the retina:

$$A = [2\,\rho_a + \gamma_a = (1/20)\,\beta_a + A_S + n]\,N_{b\,b} \qquad *$$

$$A = [2\,\rho_a + \gamma_a + (1/20)\,\beta_a + A_S + n]\,N_{b\,b}$$

where n is a constant representing noise and N_{bb} is a parameter that allows for the effect of the luminance factor of the background. These four signals, A, C_1, C_2, and C_3, are then used to formulate predictors for hue, brightness, lightness, saturation, chroma, and colorfulness.

Achromatic colors are those that do not exhibit a hue (such as whites, greys, and blacks). The criterion adopted for achromacy is that $\rho_a = \gamma_a = \beta_a$, and hence the three color difference signals, C_1, C_2, and C_3, are all zero. The chromatic response then increases as C_1, C_2, and C_3, become increasingly different from zero.

Constant hue corresponds to C_1, C_2, and C_3 being in constant ratios to each other. The unique hues are defined as corresponding to the following ratios:

Unique red: $C_1 = C_2$

Unique green: $C_1 = C_3$

Unique yellow: $C_1 = C_2/11$

Unique blue: $C_1 = C_2/4$

Brightness depends on the achromatic signal, A (together with a small contribution from the chromatic response of the cones), with due allowance being made for the effects of the surround. Lightness is a function of the brightness of a color relative to that of the reference white.

Saturation is represented by the chromatic response relative to the sum of the three cone responses, $\rho_a + \gamma_a + \beta_a$; chroma by saturation with due allowance being made for the reduction in colorfulness that accompanies reductions in brightness relative to that of the reference white; and colorfulness by chroma with due allowance being made for the reduction in colorfulness that accompanies reductions in level of illumination.

Details of the input data required to use the model, and the steps for making the calculations, are given below.

Testing the Model Predictions

One way of recording observers' perceptions of color appearance is to use magnitude estimation. In this technique observers use numbers to express the magnitudes of different percepts, such as hue, lightness, and colorfulness. In the case of hue, the apparent percentage content of two of the appropriate neighboring unique hues, red, yellow, green, and blue are used; in the case of lightness, the apparent location on a scale extending from zero for a perfect imaginary black to 100 for the reference white is used; in the case of colorfulness, the apparent location on a scale from zero for whites, greys, and blacks, to larger numbers for colors that exhibit hue, is used.

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In one very extensive investigation using this technique[3,4], hue, lightness, brightness, and colorfulness were scaled for related colors seen under a very wide variety of viewing conditions; these included: reflecting samples seen in an illuminated viewing booth; self-luminous samples displayed on a monitor; transmitting samples in large transparencies viewed on a light box; and transmitting samples in 35 mm slides projected in a dark room. The scalings obtained, referred to as the LUTCHI data base, have been used to determine the accuracy with which the Hunt 94 model predicts the scaled percepts, using percentage coefficients of variation (CVs). These CVs are calculated as 100 times the root-mean square of the differences between the predictions and the experimental results, divided by the average of the experimental results. The CV results are summarised in Table I, and are about 8 for hue, 12 for lightness, 11 for brightness, and 18 for colorfulness[5]. These values are similar to those obtained when the difference between a single observer's results are compared to those for the average of six observers. Observers' consistency in scaling was thus best for hue, worst for colorfulness, and intermediate for lightness, and for brightness, and this was also true of the predictions given by the model.

Table I

AVERAGE CVs FOR DIFFERENT OBSERVING CONDITIONS AND OBSERVER CONSISTENCY

	Hue	Lightness	Brightness	Colorfulness
Booth & Monitor	8	11	-	18
Booth at six levels (omitting lowest level)	8	14	11	22 (18)
Large transparencies	7	10	-	18
Projected slides	7	12	-	18
One observer compared to the average for six observers	8	13	10	17

Input Data Needed for the Model

The following input data are needed:

Chromaticity co-ordinates, *x,y*, and luminance factors, *Y*, in the illuminant considered:

Illuminant	x_I, y_I
Adapting field	x_A, y_A
Background	x_b, y_b, Y_b
Reference white	x_W, y_W, Y_W
Samples:	x , y , Y

By the adapting field is meant the total environment of the color element considered, extending to the limit of vision in all directions. By the background is meant the environment of the color element considered, extending typically for about 10° from the edge of the element in all, or most directions. If the adapting field is a typical average scene, or generally white, grey, or black, it is usually acceptable to take x_A , y_A as the same as x_I , y_I. If the background is a typical average scene, or generally white, grey, or black, x_b, y_b can be taken as the same as x_I, y_I, and a nonselective neutral can then be taken as the reference white and hence x_W, y_W are also the same as x_I, y_I; if this neutral is the perfect diffuser, then $Y_W = 100$. If the background is a typical average scene, Y_b can be taken as *20;* if the background is white, grey, or black, then Y_b is the value of Y for the background considered.

Luminances of Stimuli, and Scotopic Data:

Photopic luminance of reference white in cd/m^2: $L_W = L_P Y_W / 100$

where L_P is the luminance of the perfect diffuser in cd/m^2; $L_P = E/\pi$ where E is the illuminance in lux. (The photopic luminances, L, of the samples, in cd/m^2, are given by $L = L_P Y/100$.)

Photopic luminance of adapting field in cd/m^2: L_A

If the value, L_A, is not available, $L_W/5$ can be used as an approximation.

Scotopic luminance of adapting field in scotopic cd/m^2: L_{AS}

If the value, L_{AS} is not available, an approximation to it can be derived from L_A as:

$L_{AS}/2.26 = L_A[(T/4000) - 0.4]^{1/3}$ where T is the correlated color temperature of the illuminant. $L_{AS}/2.26$ is used throughout the model instead of L_{AS}, because $L_{AS}/2.26 = L_A$ for the equi-energy stimulus S_E. In the above formula this is achieved by putting $T = 5600$ for S_E .

Scotopic luminances relative to reference white: S/S_W

If the scotopic values, S/S_W, are not available, the equivalent photopic values, Y/Y_W, can be used instead as an approximation.

Values of the chromatic and brightness surround induction factors:

Chromatic surround induction factor: N_c
Brightness surround induction factor: N_b

If optimised values, N_c and N_b, are not available, the following values can be used:

	N_c	N_b
Small areas in uniform light backgrounds and surrounds	1.0	300
Normal scenes	1.0	75
Television and VDU displays in dim surrounds	1.0	25
Large transparencies on light boxes	0. 7	25
Projected photographs in dark surrounds	0. 7	10

Values of the chromatic and brightness background induction factors:

Chromatic background induction factor: N_{cb}
Brightness background induction factor: N_{bb}

If optimised values, N_{cb} and N_{bb}, are not available, the following values can be used:

$$N_{cb} = 0.725\,(Y_W/Y_b)^{0.2}$$
$$N_{bb} = 0.725\,(Y_W/Y_b)^{0.2}$$

Steps for the Calculations

Step 1 Calculate X, Y, Z for the reference white, and for the samples.

$X = xY/y \quad Y = Y \quad Z = (1 - x - y)\, Y/y$

Step 2. Calculate ρ, γ, β for the reference white, and for the samples.

$$\rho = 0.38971X + 0.68898\,Y - 0.07868Z$$

$$\gamma = -0.22981X + 1.18340Y + 0.04641Z$$

$$\beta = 1.00000Z$$

Step 3. Calculate ρ/ρ_W, γ/γ_W, β/β_W for the samples.

ρ_W, γ_W, β_W are the values of ρ, γ, β for the reference white.

Step 4. Calculate F_L

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

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

Step 5. Calculate F_ρ, $F\gamma$, F_β

$$h_\rho = 3\rho_W/\,(\rho_W + \gamma_W + \beta_W)$$

$$h_\gamma = 3\gamma_W/(\rho_W + \gamma_W + \beta_W)$$

$$h_\beta = 3\beta_W/\,(\rho_W + \gamma_W + \beta_W)$$

$$F_\rho = (1 + L_A{}^{1/3} + h_\rho) / (1 + L_A{}^{1/3} + 1/\,h_\rho)$$
$$F_\gamma = (1 + L_A{}^{1/3} + h_\gamma) / (1 + L_A{}^{1/3} + 1/h_\gamma)$$
$$F_\beta = (1 + L_A{}^{1/3} + h_\beta) / (1 + L_A{}^{1/3} + 1/h_\beta)$$

If the color of the illuminant is discounted, F_ρ, F_γ and F_β are all set at unity.

Step 6. Calculate ρ_D, γ_D, β_D

$$\rho_D = \pounds_n[\,(Y_b/Y_W)F_LF_\gamma] - \pounds_n[\,(Y_b/Y_W)\,F_LF_\rho]$$

$$\gamma_D = 0$$

$$\beta_D = \pounds_n[\,Y_b/Y_W)\,F_LF_\gamma] - \pounds_n[\,(Y_b/Y_W\,F_LF_\beta\,]$$

where $\quad \pounds_n[I] = 40\,[I^{0.73} / (I^{0.73} + 2)\,]$

If there is no Helson-Judd effect, ρ_D, γ_D, and β_D are all set at zero. (If F_ρ, F_γ, and F_β are all set at unity, ρ_D, γ_D, and β_D all become zero as a consequence).

Step 7. Calculate ρ_a, γ_a, β_a

$$\rho_a = B_\rho\,[\pounds_n\,(F_LF_\rho\,\rho/\rho_W) + \rho_D] + 1$$

$$\gamma_a = B_\gamma\,[\pounds_n\,(F_LF_\gamma\,\gamma/\gamma_W) + \gamma_D\,] + 1$$

$$\beta_a = B_\beta\,[\pounds_n\,(F_LF_\beta\,\beta/\beta_W) + \beta_D\,] + 1$$

where

$$B_\rho = 10^7/\,[\,10^7 + 5L_A\,(\,\rho_W/\,100)\,]$$

$$B_\gamma = 10^7/\,[\,10^7 + 5L_A\,(\,\gamma_W/\,100)\,]$$

$$B_\beta = 10^7/\,[\,10^7 + 5L_A\,(\,\beta_W/\,100)\,]$$

and

$$\pounds_n[\,I] = 40\,[I^{0.73} / (I^{0.73} + 2)\,]$$

Step 8. Calculate A_a, C_1, C_2, C_3

$$A_a = 2\rho_a, + \gamma_a + (1/20)\,\beta_a - 3.05 + 1$$

$$C_1 = \rho_a - \gamma_a$$

$$C_2 = \gamma_a - \beta_a$$

$$C_3 = \beta_a - \rho_a$$

Step 9. Calculate h_s

$$h_s = \arctan\{\,[\,1/2\,(C_2\text{-}C_3)/\,4.5]\,/\,[\,C_1\text{-}(\,C_2/11)]\}$$

$$= \arctan\,(t/p)$$

where ‘arctan’ means ‘the angle whose tangent is’. h_s Iies between 0° and 90° if t and p are both positive; between 90° and 180° if t is positive and p is negative; between 180° and 270° if t and p are both negative; and between 270° and 360° if t is negative and p is positive.

Step 10. Calculate the hue quadrature H

$$H = H_1 + \frac{100[(h_s - h_1)/e_1]}{[(h_s - h_1)/e_1 + (h_2 - h_s)/e_2]}$$

where H_1 is either 0, 100, 200, or 300, according to whether red, yellow, green, or blue, respectively, is the hue having the nearest lower value of h_s. The values of h_s and e_s, for the four unique hues are:

	Red	Yellow	Green	Blue
h_s	20.14	90.00	164.25	237.53
e_s	0.8	0.7	1.0	1.2

e_1 and h_1 are the values of e_s and h_s, respectively, for the unique hue having the nearest lower value of h_s; and e_2 and h_2 are these values for the unique hue having the nearest higher value of h_s.

Step 11. Calculate the Hue Composition, H_C

Where Hp is the part of H after its hundreds digit, If

$H = Hp$, the Hue Composition is
Hp Yellow, 100 – Hp Red

$H = 100 + Hp$, the Hue Composition is
Hp Green, 100 – Hp Yellow

$H = 200 + Hp$, the Hue Composition is
Hp Blue, 100 – Hp Green

$H = 300 + Hp$, the Hue Composition is
Hp Red, 100 – Hp Blue

Step 12. Calculate e_s

$$e_s = e_1 + (e_2 - e_1)(h_s - h_1) / (h_2 - h_1)$$

where e_1 and h_1 are the values of e_s, and h_s, respectively, for the unique hue having the nearest lower value of h_s; and e_2 and h_2 are these values for the unique hue having the nearest higher value of h_s.

Step 13. Calculate F_t

$$F_t = L_A / (L_A + 0.1)$$

Step 14. Calculate the yellowness-blueness, M_{YB}, the redness-greenness, M_{RG}, the chromatic response, M, the relative yellowness-blueness, m_{YB}, the relative redness-greenness, m_{RG}, and the saturation, s

$$M_{YB} = 100 [1/2 (C_2 - C_3) / 4.5] [e_s (10 / 13) N_c N_{cb} F_t]$$

$$M_{RG} = 100 [C_1 - (C_2/11)] [e_s (10 / 13) N_c N_{cb}]$$

$$M = (M_{YB}^2 + M_{RG}^2)^{1/2}$$

$$m_{YB} = M_{YB} / (\rho_a + \gamma_a + \beta_a)$$

$$m_{RG} = M_{RG} / (\rho_a + \gamma_a + \beta_a)$$

$$s = 50M / (\rho_a + \gamma_a + \beta_a)$$

Step 15. Calculate F_{LS}

$$F_{LS} = 3800 j^2 (5L_{AS}/2.26) + 0.2 (1 - j^2)^4 (5L_{AS}/2.26)^{1/6}$$

where

$$j = 0.00001 / [(5 L_{AS} / 2.26) + 0.00001]$$

Step 16. Calculate A_S

$$A_S = B_S (3.05)[f_n (F_{LS} S/S_W)] + 0.3$$

where

$$B_S = 0.5/\{1 + 0.3 [(5L_{AS}/2.26)(S/S_W)]^{0.3}\} + 0.5/\{1 + 5 [5L_{AS}/2.26]\}$$

and

$$f_n[I] = 40[I^{0.73}/(I^{0.73} + 2)]$$

Step 17. Calculate A

$$A = N_{bb}[A_a - 1 + A_s - 0.3 + (1^2 + 0.3^2)^{1/2}]$$

Step 18. Calculate $A + (M/100)$

$$A + (M/100)$$

Step 19. Calculate Q and Q_W

$$Q = \{ 7 [A + (M/100)] \}^{0.6} N_1 - N_2$$

where

$$N_1 = (7A_W)^{0.5} / (5.33 N_b^{0.13})$$

$$N_2 = (7A_W N_b^{0.362}) / 200$$

and A_W is the value of A for the reference white.

Step 20. Calculate J

$J = 100(Q/Q_W)z$ *

$$J = 100(Q/Q_W)^z$$

where Q_W is the value of Q for the reference white, and

$$z = 1 + (Y_b / Y_W)^{1/2}$$

Step 21. Calculate the chroma, C_{94}, and the colorfulness, M_{94}

$$C_{94} = 2.44 s^{0.69} (Q/Q_W)^{Yb/Yw} (1.64 - 0.29^{Yb/Yw})$$

$$M_{94} = F_L^{0.15} C_{94}.$$

Step 22.

Tabulate the values of H, H_C, M_{94}, s, Q, J, and C_{94}.

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