APPEARANCE MODELLING

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Abstract: When images are displayed in different media, the viewing conditions are often different. This means that conventional colorimetry is an inadequate basis for comparing the images. Models of color vision have therefore been devised that take account of the effects of many of the viewing conditions. The models can then be used to predict the appearances of colors displayed in different media; criteria for equality of appearance can then be determined, and differences in appearance evaluated in a meaningful way. One such model is described. Its predictions for samples, seen by reflection, by projection, and by display on television-type monitors, are reviewed and discussed.

INTRODUCTION

It has long been recognized that the effects of adaptation by the eye to light of different luminances and chromaticities are important in color reproduction. For instance, if the reproduction of a sunlit scene is viewed in tungsten light, the correct chromaticities in the reproduction have to be more orange than those in the original. The CIELab and CIELUV color systems make some allowance for this by the incorporation of reference whites; but these systems are only intended to be used with illuminants whose chromaticities are not too different from those of daylight, and it cannot be assumed that they will be satisfactory for other illuminants. Furthermore, these color spaces do not make any allowances for the effects of differences in the backgrounds and surrounds to the colors or in their luminance levels. Some more comprehensive system of color evaluation is therefore necessary when dealing with colors displayed in different media, and one approach is to use a model of color vision that predicts the appearances of colors in different viewing situations. Criteria for equality of appearance can then be determined, and differences in appearance evaluated in a meaningful way (Pointer, 1986a; Pointer, 1986b; Wood, Pointer, Attridge and Jacobsen, 1987; Attridge, Pointer, and Reid, 1991).

Models of color vision suitable for this purpose have been described by Nayatani and his co-workers (Nayatani, Takahama, and Sobagaki, 1986; Nayatani, Hashimoto, Takahama, and Sobagaki, 1987; Nayatani, Takahama, Sobagaki, and Hashimoto, 1990), and by the writer (Hunt, 1982; Hunt and Pointer, 1985; Hunt, 1987; Hunt, 1990; Hunt, 1991). In this paper, the latter model (as applied to related colors) will be described briefly, together with some of its predictions for samples seen by reflection, by projection, and by display on television-type monitors.

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Visual Areas in the Observing Field

Five different visual fields for related colors are recognized in the model.

The color element considered:

typically a uniform patch of about 2° angular subtense.

The proximal field:

the immediate environment of the color element considered, extending typically for about 2° from the edge of the color element considered in all or most directions.

The background:

the environment of the color element considered, extending typically for about 10° from the edge of the proximal field in all, or most directions. When the proximal field is the same color as the background, the latter is regarded as extending from the edge of the color element considered.

The surround:

the field outside the background.

The adapting field:

the total environment of the color element considered, including the proximal field, the background, and the surround, and extending to the limit of vision in all directions.

The visual patterns of scenes viewed in practice are almost infinitely variable; but the regime of fields described above is an attempt to simplify the situation sufficiently to make it feasible for modelling, while making it possible to include the most important factors that affect color appearance.

The Responses of the Cones

The amounts, ρ, γ, and β, of radiation usefully absorbed per unit area of the retina by the three different types of cone in a given state of adaptation, for light incident on the cornea, are derived as follows:

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

$$\gamma = -0.22981X + 1.18340Y + 0.04641Z \qquad (1)$$

$$\beta = 1.00000Z$$

The co-efficients used in the above equations are such that the values of ρ, γ, and β are equal to one another for the equi-energy stimulus, S_E. If the color element considered has an angular subtense of more than 4°, the tristimulus values of the CIE 1964 Supplementary Standard Colorimetric Observer are used instead of X, Y, and Z, and the subscript 10 is attached to all the symbols used.

Under a given set of viewing conditions, there will be a predictable relationship between the responses of the cones and the intensity of the stimulus. When the intensity of the stimulus is very low, noise in the system must prevent extremely small cone responses from being significant; and when the intensity of the stimulus is very high, the response must eventually reach a maximum level beyond which no further increase is possible (Baylor, 1987). A hyperbolic function is therefore chosen to represent the response for the cones (as suggested by Seim & Valberg, 1986, and for which there is physiological evidence as described by Boynton and Whitten, 1970, and by Valeton and Van Norren, 1983). The responses given by the three different types of cone in a given state of adaptation are then formulated as:

$$f_n(\rho) + 1 = 40\,[\rho^{0.73}/(\rho^{0.73} + 2)] + 1$$

$$f_n(\gamma) + 1 = 40\,[\gamma^{0.73}/(\gamma^{0.73} + 2)] + 1 \qquad (2)$$

$$f_n(\beta) + 1 = 40\,[\beta^{0.73}/(\beta^{0.73} + 2)] + 1$$

The + 1 terms represent the noise. These responses give maximum values of 41 and minimum values of 1. In Figure 1, log $[f_n(\rho) + 1]$ is plotted against log ρ. The responses $f_n(\gamma) + 1$ and $f_n(\beta) + 1$ would be represented by similar graphs. It is clear from the figure that, over the central part of the curve, the response approximates a square root relationship, as shown by the broken line, and this has been shown to lead to a simple prediction of constant hue in chromaticity diagrams (Hunt, 1982).

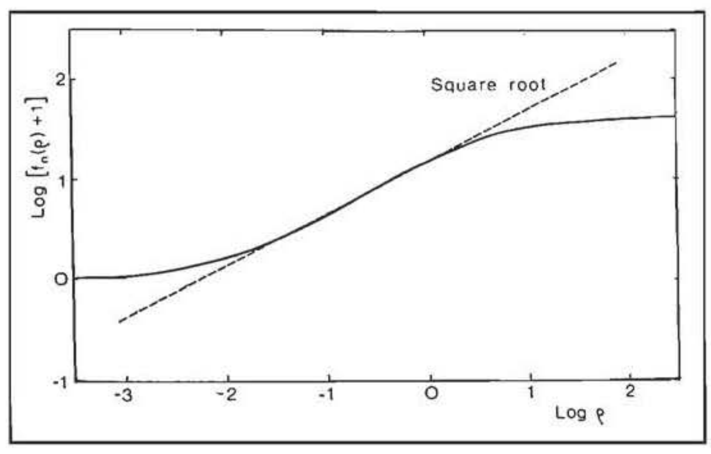

Figure 1. Cone response function. The log of the function, $\log[f_n(\rho) + 1]$, is plotted against the log of the radiation, ρ, usefully absorbed.

Adaptation

The actual response produced by the cones is dependent, not only on the intensity of the stimulus, but also on the state of adaptation of the eye. The cone responses after adaptation are formulated as:

$$\begin{aligned} \rho_a &= \beta_\rho[f_n(F_L F_\rho \rho/\rho_w) + \rho_D] + 1 \\ \gamma_a &= \beta_\gamma[f_n(F_L F_\gamma \gamma/\gamma_w) + \gamma_D] + 1 \\ \beta_a &= \beta_\beta[f_n(F_L F_\beta \beta/\beta_w) + \beta_D] + 1 \end{aligned} \tag{3}$$

where the function $f_n(I)$ is again of the form:

$$f_n(I) = 40[I^{0.73}/(I^{0.73} + 2)] \tag{4}$$

The factors, ρ_w, γ_w, and β_w, are the ρ, γ, and β values for the reference white. The divisions by ρ_w, γ_w, and β_w provide a Von Kries type of allowance for adaptation, whereby complete compensation would be made for changes in the level and color of the illumination. The other factors in the above equations make allowance for the fact that such compensation is usually only partial (Hunt, 1991); these factors will be discussed briefly in a later section.

Criteria for Achromacy and for Constant Hue

There is a great deal of evidence that the responses from the three different types of cone are compared by neurons in the retina that result in *color difference* signals being formed for subsequent transmission along the optic nerve fibers to the brain. These color difference signals are formulated as:

$$\begin{aligned} C_1 &= \rho_\alpha - \gamma_\alpha \\ C_2 &= \gamma_\alpha - \beta_\alpha \\ C_3 &= \beta_\alpha - \rho_\alpha \end{aligned} \tag{5}$$

Achromatic colors are those that do not exhibit a hue (such as whites, greys, and blacks). The criterion adopted for achromacy is:

$$\rho_\alpha = \gamma_\alpha = \beta_\alpha \tag{6}$$

and hence

$$C_1 = C_2 = C_3 = 0 \tag{7}$$

Colorfulness then increases as C_1, C_2, and C_3 become increasingly different from zero.

The criterion for constant hue is:

$$C_1 \text{ to } C_2 \text{ to } C_3 \text{ in constant ratios.} \tag{8}$$

Criteria for unique hues will be considered after the next sections which deal with various effects of adaptation.

Adaptation-Reducing Factors

Descriptions will now be given of the natures of the factors in equations (3) for reducing the effects of adaptation (details of these factors can be found in Hunt, 1991).

The factors, B_ρ, B_γ, and B_β, provide reductions in cone responses at very high levels of illumination, where appreciable bleaching of the cone pigments occurs.

The factor, F_L, provides allowance for the level of illumination. In Figure 2, ρ_α is plotted against $\log(5L_A\rho/\rho w) = \log I$, where L_A is the luminance of the adapting field. The reason for using the factor 5 is that for related colors in typical viewing conditions, the luminance of a reference white is often about five times that of the adapting field, and hence $5L_A$ can often be regarded as the luminance of a reference white. If $5L_A$ is the luminance of the reference white, and the sample has the same chromaticity as the reference white, then $5L_A\rho/\rho w$ is equal to the luminance of the sample. The curves shown in Figure 2 are for values of $\log(5L_A)$ equal to 8, 7, 6, 5, 4, 3, 2, 1, and 0 log cd/m^2 (full lines), and for dark adaptation (broken line).

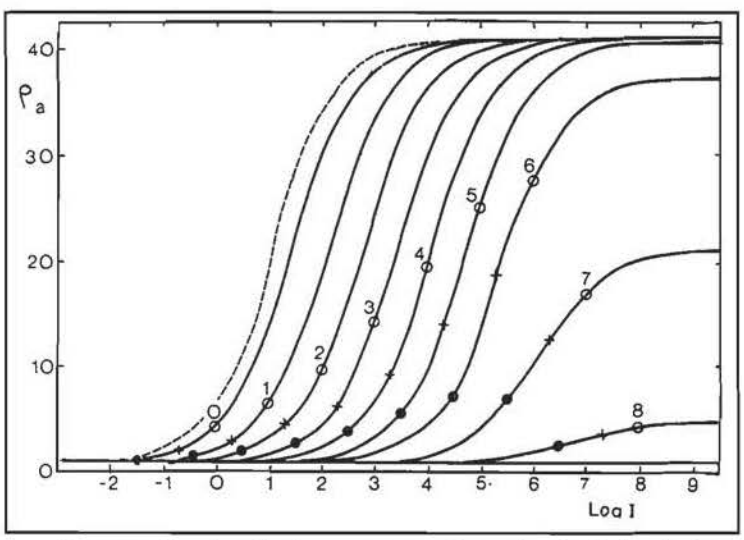

Figure 2. Response functions for the ρ cones at different levels of adapting luminance.

Let us consider the curve labelled 3; this is for $\log(5L_A)$ equal to 3, and the open circle on this curve is for a color having the same value of ρ/ρ_w as for the reference white, and the filled circle for a color having ρ/ρ_w equal to 0.03162 times that of the reference white (that is, 1.5 less on the log scale). Relationships similar to those shown in the graph in Figure 2 also apply for γ_a and β_a. Hence, when $\log(5\,L_A) = 3$, the reference white would be represented by points at the open-circle positions on curve 3 in all three graphs, and a color having the same chromaticity as the reference white, but a luminance 0.03162 times (1.5 log units) less, by points at the filled circles on curve 3 in all three graphs. The part of curve 3 between the open and filled points therefore represents the range of colors between white (the reference white) and a black (of luminance 3.162% of that of the reference white), when $\log(5L_A)$ is equal to 3 log cd/m^2. The position of the adapting field, L_A (taken as 1/5, that is 20%, of the luminance of the white, or 0.7 less on the log scale), is shown by the plus sign (+) on curve 3.

The other curves of the figure similarly represent the same range of colors for values of $\log(5L_A)$ that become progressively smaller as the curve is displaced towards the left, and higher towards the right. Physiological studies show similar families of curves (Valeton and Van Norren, 1983).

The lower maxima of curves 6, 7, and 8 in Figure 2 are caused by the cone bleach factors. For the other curves, the following general features can be seen. As the luminance of the adapting field, L_A, decreases, the curves move to the left, indicating increasing sensitivity. But this movement is insufficient to provide full compensation, and hence the positions of the points representing white (0), the adapting field (+), and black (•) gradually move down each curve to regions of lower slope. This results in reductions in the differences in response between whites, adapting fields, and blacks. For colors, this results in reductions in the color difference signals, C_1, C_2, and C_3, so that colorfulness should decrease; in practice colors do become less colorful when viewed in dimmer lighting. Similarly the low-contrast 'toe' of each curve predicts that, for each level of illumination, colors of a given chromaticity should decrease in colorfulness as the luminance factor is decreased; this is also found in practice. It is also clear from Figure 2 that the slopes of the curves near the black points (•) become very low for the curves towards the left; and this predicts that dark colors should be difficult to distinguish in dim lighting; this is also found in practice. For stimuli of luminances very much higher than that of the reference white, the responses may approach the maximum level, in which case they will also tend to be reduced in colorfulness.

The factors F_ρ, F_γ, and F_β allow for the fact that adaptation to lights of different colors becomes less and less complete as the purity of the color of the light (relative to the equi-energy stimulus, S_E) increases, and more and more complete as the luminance increases.

When observers attempt to identify the colors of surface objects, they can sometimes make perceptual allowance for the color of the prevailing illumination (McCann and Houston, 1983; Arend and Reeves, 1986). For instance, if an observer passes from an environment in which the illuminant is a daylight to one in which the illuminant is a tungsten light, then, although a piece of white paper generally appears to be yellowish in the tungsten light, it may still be correctly identified as a white, not as a yellow, object. This effect is sometimes referred to as *discounting the color of the illuminant*. This mode of perception can be modelled by setting F_ρ, F_γ, and F_β all equal to unity.

When the chromacity of the illuminant is substantially different from that of the equi-energy stimulus, S_E, white colors tend to appear to be tinged with the hue of the illuminant, and very dark greys with the complementary hue; this is usually referred to as the *Helson-Judd effect*. The factors ρ_D, γ_D, and β_D make allowance for this. They ensure that a grey having the same relative luminance factor as the background is predicted to appear achromatic whatever the color of the illuminant. If the mode of perception involves no Helson-Judd effect, ρ_D, γ_D, and β_D, can all be set to zero.

Use of a Modified Reference White

When simultaneous contrast occurs, the proximal field, which provides the immediate environment, causes the appearance of the color element considered to move towards the color that is opposite in hue, saturation, and lightness to the color of the proximal field. But when the angular subtense of the color element considered becomes less than about a third of a degree, instead of simultaneous contrast, assimilation occurs, the appearance of the color then tending to move towards that of the proximal field. These effects are modelled by computing a modified reference white. (For details, see Hunt, 1991).

Criteria for Unique Hues

There are four unique hues: red, green, yellow and blue. The model predicts these as occurring at the following ratios of C_1 to C_2 or C_3 (because $C_1 + C_2 + C_3 = 0$, if one of these ratios is constant, the other will also be constant, and need not be specified in addition):

Unique red	$C_1 = C_2$	
Unique green	$C_1 = C_3$	
Unique yellow	$C_1 = C_2/11$	(9)
Unique blue	$C_1 = C_2/4$	

Hue angle, h_s

A measure of hue denoted as the *hue-angle*, h_s, is defined as:

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

$$= \arctan(t/t') \qquad (10)$$

where 'arctan' means 'the angle whose tangent is.' The quantity h_s lies between 0° and 90° if t and t' are both positive; between 90° and 180° if t is positive and t' is negative; between 180° and 270° if t and t' are both negative; and between 270° and 360° if t is negative and t' is positive.

Correlate of Colorfulness

Correlates of yellowness-blueness, M_{YB}, and redness-greenness, M_{RG}, are formulated as follows:

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

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

where e_s is an eccentricity factor (that represents the different colorizing weights of red, yellow, green and blue unique hues), N_c is a chromatic surround induction factor, N_{cb} is a chromatic background induction factor, and F_t is a low-luminance tritanopia factor (for details of these factors, see Hunt, 1991). The constant, 100, is included to give convenient numbers. Correlates of colorfulness, M, and saturation, s, are then given by

$$M = (M_{YB}^2 + M_{RG}^2)^{1/2} \quad (12)$$

$$s = 50M/(\rho_\alpha + \gamma_\alpha + \beta_\alpha) \quad (13)$$

The constant, 50, is included to give convenient numbers.

Correlates of Hue, H and H_c

In Figure 3 (left half) is shown a plot of $(1/2)(C_2 - C_3)/4.5$ against $C_1 - (C_2/11)$. In this figure, the value of h_s is the angle between a horizontal line drawn from the origin towards the right and the line joining the origin to the point representing the color considered. The positions of the unique hue lines are shown in this diagram by the full lines, R, Y, G, and B.

Hue can also be expressed in terms of the proportions of the unique hues perceived to be present, and the model provides a correlate of hue expressed in this way, *hue quadrature*, H (Hunt, 1991). H is equal to 0 for unique red, 100 for unique yellow, 200 for unique green, and 300 for unique blue. This is shown in the right-hand half of Figure 3.

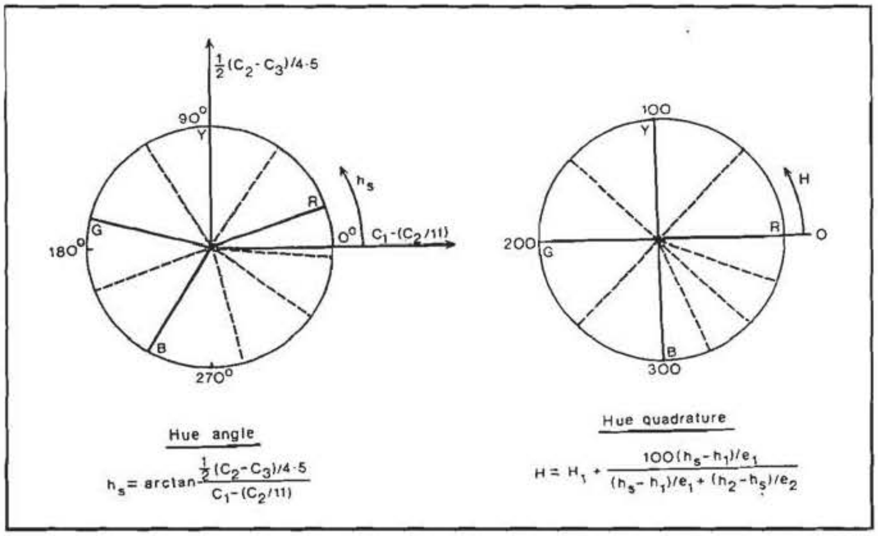

Figure 3. Left: hue angle, h_s, shown in a plot of (1/2) $(C_2 - C_3)/4.5$ against $C_1 - (C_2/11)$. Right: hue quadrature, H.

In Figure 3, the angular positions of the lines representing colors that are perceptually midway between adjacent pairs of unique hues (that is, appearing to contain 50% of each of the two hues) are shown by the broken lines; these broken lines are not at equal angular spacings between the lines representing the unique hues in the figure on the left, because of the effect of the different colorizing weights of the red, yellow, green, and blue unique hues. (In the case of the red-blue quadrant, because of its larger size in the diagram, broken lines are shown that divide it into four perceptually equal parts.) In the case of hue quadrature, H (on the right), the effects of these weights have been included in the derivation of H (the formula for which includes e_1 and e_2 the values of e_s for the two unique hues involved), and hence the broken lines are spaced at regular intervals. However, because unique red and green are placed opposite one another, with unique yellow and blue also opposite one another, and at right angles to the red-green axis, the four quadrants do not represent equal *differences* in hue; while the perceptual difference between the pairs of unique hues red and yellow, yellow and green, and green and blue, are not too different, the perceptual difference between blue and red is about twice as large, and this is represented by the crowding of the three broken lines in this quadrant. However, hue angle (on the left) represents differences in hue more uniformly. The spacing of hue angle (shown on the left) is similar to that of the hues in the Munsell system, while the spacing of hue quadrature (shown on the right) is similar to that of the hues in the NCS system.

H can be expresssed both as a number, and as *hue composition*, H_c, in terms of the percentages of the component hues. When the two right-hand digits are more than 50, they indicate the main hue percentage, and the remaining percentage is that of the minor hue; for example, if H = 262, the component hues in percentages are 62 Blue and 38 Green, which is abbreviated to 62B 38G. If the two right-hand digits are less than 50, they represent the minor hue percentage, and the remaining percentage is that of the major hue; for example, if H = 231, the hue composition is 69 Green 31 Blue, or 69G 31B.

Comparison with the Natural Color System

In Figure 4, the full lines show the loci of constant hue and saturation predicted by the model for a high level of Standard Illuminant C adapting luminance, such as L_A equal to 200 cd/m^2; the broken lines show the results obtained experimentally in the Natural Color System (NCS), and the two sets of lines are seen to be broadly similar. The unique hue loci are labelled R, Y, G, and B; the intermediate hue loci divide each quadrant into perceptually equal segments of hue. The contours shown are for values of the saturation, s, of the model equal to 60, 120, 180, and 320, and for values of NCS chromaticness, c, equal to 30, 50, 70, and 90.

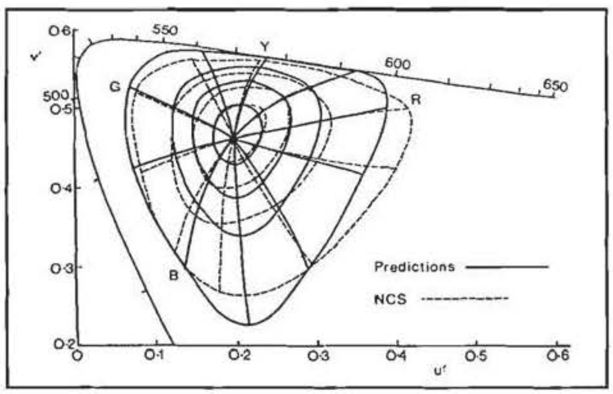

Figure 4. Constant hue loci, and constant saturation contours, predicted by the model (full lines) compared with those of the NCS (broken lines) for Standard Illuminant C.

The Achromatic Response, A

In addition to the color difference signals, the retina sends to the brain an achromatic signal (for details, see Hunt 1991). This is modelled as:

$$A = N_{bb}[A_a - 1 + A_S - 0.3 + (1^2 + 0.3^2)^{1/2}] \tag{14}$$

Where A_a represents the contributions from the cones, and A_S that from the rods; N_{bb} is a factor to allow for the brightness induction of the background. To allow for the fact that, compared to the number of γ cones, there are more ρ cones and many fewer β cones (Walraven and Bouman, 1966), A_a is given by

$$A_a = 2\rho_a + \gamma_a + (1/20)\beta_a - 3.05 + 1 \tag{15}$$

Correlate of Brightness, Q

The brightness response is regarded as being mainly a function of the achromatic signal; but a small contribution from the color difference signals is added so that allowance can be made for the increase in brightness with increasing purity for colors of constant luminance (the Helmholtz-Kohlrausch effect). Hence, the brightness response in the model depends on:

$$A + (M/100) \tag{16}$$

The correlate of brightness, Q, is then evaluated as:

$$Q = [7\,(A + (M/100))]^{0.6} N_1 - N_2 \tag{17}$$

where

$$N_1 = (7A_w)^{0.5}/(5.33 N_b^{0.13}) \tag{18}$$

$$N_2 = 7 A_w N_b^{0.362}/200 \tag{19}$$

A_w is the value of A for the reference white, and N_b is the brightness surround induction factor, which has the following values (the values of N_c, the chromatic surround induction factor introduced earlier are also listed here for convenience):

	N_b	N_c
Small areas in uniform light backgrounds and surrounds	300	1.0
Normal scenes	75	1.0
Television and VDU displays in dim surrounds	25	0.95
Projected photographs in dark surrounds	10	0.9
Arrays of adjacent colors in dark surrounds	5	0.75

Correlate of Lightness

Lightness is brightness judged relative to that of the reference white. The correlate of lightness, J, is made to be dependent on the ratios of the luminance factors, Y_b of the background and Y_w of the reference white, and is evaluated as:

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

where (20)

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

Correlate of Chroma, C

The correlate of chroma, C, also includes an allowance for the luminance factor, Y_b, of the background, relative to that, Y_w, of the reference white, and is given by:

$$C = 4s^{0.69}(Q / Q_w)^{Y_b / Y_w}(1.31 - 0.31^{Y_b / Y_w}) \tag{21}$$

where s is the saturation, Q is the brightness, and Qw is the brightness of the reference white.

Correlate of Whiteness-Blackness, Q_{WB}

Nayatani and his co-workers have introduced the concept of a whiteness-blackness perception (Nayatani, Hashimoto, Takahama and Sobagaki, 1987), and the model provides a correlate of this perception as:

$$Q_{WB} = 20\,(Q^{0.7} - Q_b^{0.7}) \tag{22}$$

where Q_b is the value of Q for the background.

Comparison with Scaled Brightnesses

In Figure 5 are shown relationships between predicted brightness, Q, and stimulus intensity, I, for elements of reflection prints of real scenes viewed in typical surroundings at various levels of illumination to which the observers were adapted; N_b was put equal to 65. Log Q is plotted against log I, where I is the stimulus luminance in cd/m^2. Experimental results obtained by Bartleson (Bartleson, 1980) are shown by the circles; the curves show the predictions, when the adapting luminance is taken as one-fifth of that of the reference white (the top circle on each curve), and the colorfulness, M, is zero.

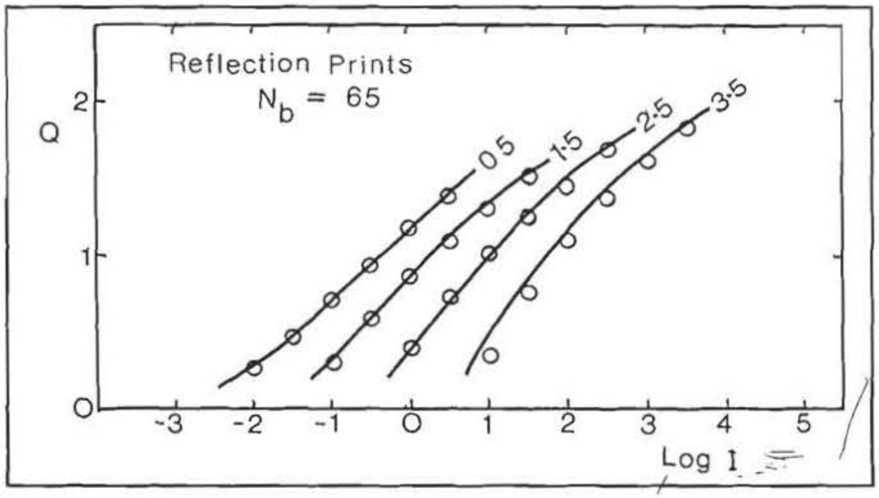

Figure 5. Log brightness, log Q, plotted against log intensity, log I (expressed as log cd/m^2 of luminance), for reflection prints seen under four different levels of illumination. Reference white luminances were such that log ($5L_A$) = 3.5, 2.5, 1.5, or 0.5 log cd/m^2.

In Figure 6, a similar comparison is shown for elements of slides of real scenes viewed when projected with dark surrounds; in this case N_b was put equal to 9.3. It is clear from Figures 5 and 6 that the quantity, Q, gives predictions in very satisfactory agreement with these experimental results.

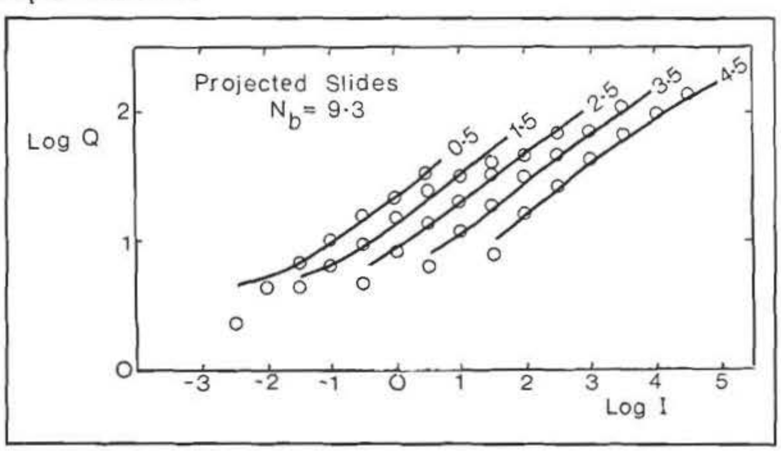

Figure 6. Same as Figure 5, but for elements of slides viewed by projection in a dark surround at five different levels of screen luminance. Screen luminances were such that log ($5L_A$) = 4.5, 3.5, 2.5, 1.5, or 0.5 log cd/m^2, where $5L_A$ was the screen luminance of the reference white in cd/m^2.

Comparison with Scaled Colors in Booths and On Monitors

In a recent investigation (MacDonald, Luo, and Scrivener, 1990; Luo, Clarke, Rhodes, Schappo, Scrivener, and Tait, 1991a and b), the appearances of colors in a viewing booth, and displayed on a shadow-mask type monitor, were studied. Predictions given by the model were compared to the results obtained by subjective scaling of hue, lightness, and colorfulness. The colors were viewed at two different levels of illumination in the booth, but at only one luminance level on the monitor (corresponding to the lower of the booth levels). In the booth, four different colors of illuminant were used: CIE Standard Illuminants D_{50} and D_{65}, White Fluorescent (WF), and CIE Standard Illuminant A (S_A); these colors were also simulated on the monitor. In the booth the colors were seen against either a grey, a white, or a black background, and these backgrounds were also simulated on the monitor. The colors on the monitor were displayed either with the simulated background going right to the edge of the display, or with a simulated white or black border.

Table I
Comparison of Model Predictions with Lutchi Scalings
Co-efficients of Variation (CV%)

Illum-inant	Back-ground	L_w cd/m^2	Mode	Hue CV	Lightness CV	Colorfulness CV	CV	C CV
D_{50}	Grey	252	B	7	14	24	22	15
		42	B	6	11	25	20	17
		44.5	M	7	9	28	19	15
		44.5	M+WB	6	9	26	16	16
		44.5	M+BB	6	8	30	20	13
	White	264	B	8	16	19	22	20
		44	B	7	15	29	21	26
		40	M	8	13	28	19	26
	Black	252	B	7	9	35	31	22
		42	B	7	11	28	26	18
		44.5	M	7	9	31	22	19
D65	Grey	243	B	6	13	18	18	15
		40.5	B	6	10	27	21	16
		40.5	M	6	12	33	20	16
		40.5	M+WB	6	9	30	18	12
WF	Grey	252	B	9	12	24	24	20
		42	B	10	11	32	27	18
		28.4	M	8	10	48	35	26
		28.4	M+WB	9	9	45	32	24
S_A	Grey	232	B	8	11	22	18	18
		42	B	14	11	22	24	18
		20.3	M	12	9	43	30	28
		20.3	M+WB	9	8	38	26	29
Average				8	11	30	23	19

B: booth. M: monitor. M+WB: monitor with white border. M+BB: monitor with black border.

Table II
Comparison of Model Predictions with Observer Consistency
Co-efficients of Variation (CV%)

	Hue	Lightness	Colorfulness		C
	CV	CV	CV	CV	CV
Model predictions compared to average experimental scalings	8	11	30	23	19
Individual observer's scalings compared to average scalings for 6 observers	9	13		18	

The results are summarized in Table I. Co-efficients of variation (CV) are given: each CV was evaluated as 100 times the-root-mean square (RMS) difference between the predictions given by the model and the experimental results, divided by the average value of the experimental results. The lower the CV values, the smaller are the differences between the predictions given by the model and the experimental results.

Two columns of figures are shown for colorfulness. The first, with an average of 30, shows the results given by the model with N_c, the chromatic surround induction factor, set equal to 1.0 for the booth and to 0.95 for the monitor. This average value of 30 is rather high, but becomes lower if different values of N_c are adopted. If, for both the booth and the monitor, N_c is 0.93 for the high luminance level and 1.18 for the low luminance level, the average reduces to 23, as shown in the second column; the model with these values of N_c is referred to elsewhere as the Hunt-ACAM model (MacDonald, Luo, and Scrivener, 1990). The CV values for the correlate of chroma, C, used in the model, are shown in the last column in Table I. Compared to the CV of 23 for Hunt-ACAM colorfulness, the CV for C is only 19; moreover, C uses the normal values of N_c, equal to 1.0 for the booth (at both luminance levels) and 0.95 for the monitor, instead of different values for the two luminance levels as in the Hunt-ACAM model.

Observers' consistency of scaling was best for hue and worst for colorfulness, and, in Table II, the average CVs for the model are compared to the CVs obtained between one observer's results and the average for six observers. These two sets of figures indicate that, for these colors, the hue, lightness, and chroma of the model predict their appearances about as closely as a single observer's results would agree with the average for six observers. This level of agreement is probably about as good as can be expected and should be useful in many practical applications.

Filtration of Projected Slides

If a uniformly colored filter is placed over the whole of a color slide, then the appearance of the slide when projected can be similar to that when it is projected without the filter; this is because the observer adapts almost completely to the different overall color of the projected image. But, if the same filter is placed over the depiction of the slide of an object comprising only a small part of the area of the slide, then the apparent color of that object in the projected image can change very dramatically. An example of these phenomena is a slide in which the picture contains a yellow cushion and a person wearing a white blouse. If a cyan filter is placed over the whole slide, the projected image, although slightly 'colder,' looks generally similar to its unfiltered projected appearance. But, if the cyan filter is placed over only the depiction on the slide of the cushion, then the apparent color of the cushion in the projected image changes from yellow to green. To test the ability of the model to predict these effects, the following colorimetric measurements (Hunt, 1979) were used as a starting point (assuming a reference white luminance, L_w, of 100.4 cd/m^2):

	L_w	Y	x	y	T
Illuminant	100.4	-	0.423	0.410	2856
Reference white	-	100.0	0.423	0.410	-
Cushion	-	70.8	0.486	0.456	-
Filtered cushion	-	21.6	0.378	0.511	-
Filtered illuminant	32.5	-	0.288	0.383	5600
Filtered reference white	-	100.0	0.288	0.383	-
Filtered cushion	-	66.7	0.378	0.511	-

The reference white used was the white blouse in the picture. T is the correlated color temperature of the illuminant in kelvin. With $N_c = 0.9$, and $N_b = 10$, the results obtained from the model were as follows:

	H_C		M	M_{RG}	M_{YB}	s	Q	J	C
Unfiltered slide									
Blouse	92Y	8R	12.0	1.1	12.0	20.1	57.4	100	16
Cushion	98Y	2G	43.9	-0.9	43.9	100.2	51.5	85	49
Filtered cushion	9Y	91G	34.9	-31.8	14.4	137.7	32.7	44	55
Filtered slide									
Blouse	91G	9B	15.0	-14.7	2.7	30.3	46.8	100	22
Cushion	78Y	22G	39.6	-8.7	38.6	117.6	41.0	83	54

It is clear from the above table of results that the model predicts that, for the unfiltered slide, the cushion appears predominantly yellow without the filter and predominantly green with it; whereas for the filtered slide, the filtered cushion appears predominantly yellow. This can also be seen from Figure 7 in which M_{YB} is plotted against M_{RG}. The points representing the different stimuli are labelled as follows: white blouse unfiltered, WB; cushion unfiltered, YC; filter over the cushion only, YC (F); white blouse with filter over the whole slide, WBF; cushion with filter over the whole slide, YCF. Figure 7 also shows that the model predicts that the white blouse should look slightly yellowish in the unfiltered slide, and slightly greenish in the filtered slide; this agrees with the fact that the unfiltered projected picture has a slightly warm appearance resulting from the use of a tungsten lamp, and the filtered picture has a slightly cold appearance resulting from the use of the cyan filter.

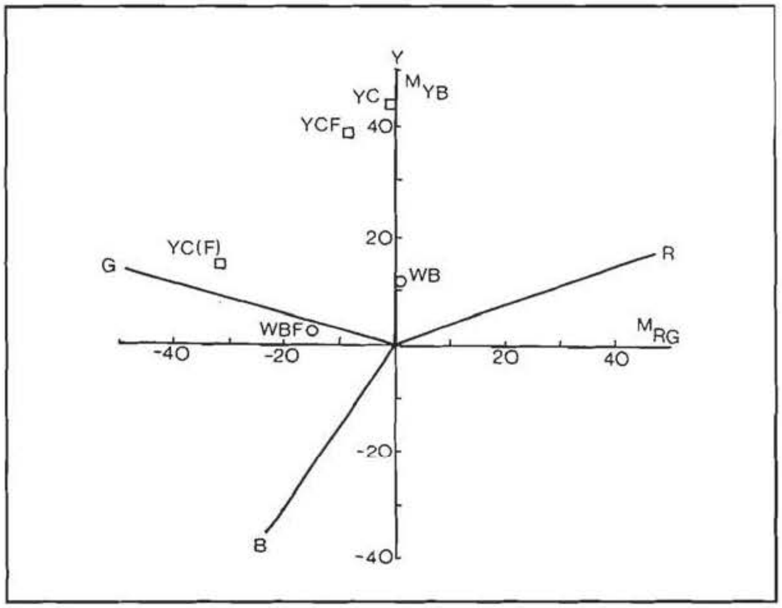

Figure 7. Color appearance diagram provided by the model in which yellowness-blueness, M_{YB}, is plotted against redness-greenness, M_{RG}.

Effect of Screen Luminance on Slides

It is a very well-known fact that projected slides exhibit better picture quality when projected at high, rather than at low, screen luminances. Bartleson quantified this effect by having observers scale relative picture excellence for various screen luminances (Bartleson, 1965). Bartleson's results for slides one stop underexposed are shown in Figure 8 by the circles. The increase in picture excellence with screen luminance is usually attributed to the resultant increases in brightness and colorfulness of the elements of the scenes. To represent this, the model was used to provide values of log (Q + M) where Q is the predicted brightness and M is the predicted colorfulness, for the filtered and unfiltered cushion in the example of slide filtration described above, but for various screen luminances. The curve in Figure 8 passes through the average values of log (Q + M) for the two colors. (An average for a wider selection of colors would have been more representative of scenes in general, but the results would no doubt have been somewhat similar to those obtained for the two colors chosen). The abscissa is $\log L_w$, where L_w is the screen luminance of the white blouse. It is clear from the similarity of the points and the curve in Figure 8 that, taking log (Q+ M) to represent picture excellence, the model gives good predictions.

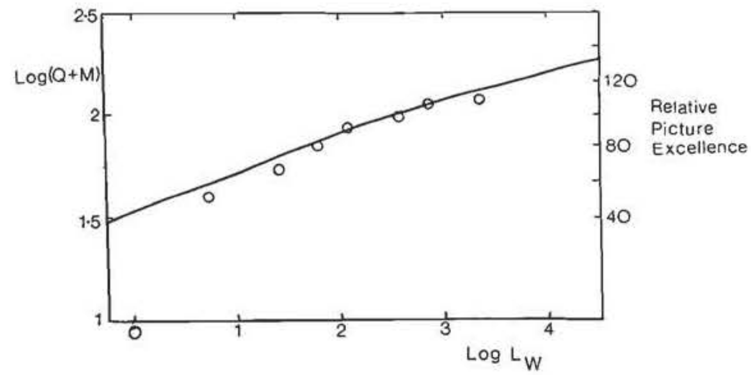

Figure 8. Curve: log (Q + M) for the average of the unfiltered and the filtered yellow cushion, plotted against log luminance (log L_w) of the reference white (the white blouse). Circles: values of relative picture excellence, obtained by Bartleson for various screen luminances, plotted against log luminance of a reference white of density 0.3.

CONCLUSIONS

A model of color vision has been shown to give reasonably good predictions of the appearance of colors seen by reflection, by projection, and by display on television-type monitors.

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