The Challenge of our Unknown Unknowns

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Abstract

Some topics in color science, for which we hardly know where to look for answers, are discussed, including the following. Why does sharpening color-matching functions lead to better chromatic adaptation transforms? Why do the unique hues occur where they do in color space? Why do effective color-difference formulas have to be so complicated? Why do bluer whites look whiter than neutral whites of the same reflectance, and why is this also true of blacks?

Introduction

There was an engineer who had an exceptional gift for fixing all things mechanical. After serving his company loyally for over 30 years, he happily retired. Several years later the company contacted him regarding a seemingly impossible problem they were having with one of their multimillion dollar machines. They had tried everything and everyone else to get the machine to work but to no avail. In desperation, they called on the retired engineer who had solved so many of their problems in the past. The engineer reluctantly took the challenge. He spent a day studying the huge machine. At the end of the day, he marked a small "x" in chalk on a particular component of the machine and stated, "This is where your problem is." The part was replaced and the machine worked perfectly again. The company received a bill for $50,000 from the engineer for his service. They demanded an itemized accounting of his charges. The engineer responded briefly: "One chalk mark $1. Knowing where to put it $49,999." There are some problems in color science needing answers, for which we don't know where to look. The title of this paper is taken from 'The Unknown' by Donald Rumsfeld[1].

As we know, there are known knowns.
  There are things we know we know.
We also know there are known unknowns.
  That is to say, we know there are some things
  we do not know.
But there are also unknown unknowns,
  the ones we don't know we don't know.

This paper completes a group of four:

2009 The Challenge of our Known Unknowns[2]
  Lack of tools for areas such as the colour
    rendering of LEDs.
2010 The Challenge of our Unknown Knowns[3]
  Lack of knowledge of items such as the *u'*,*v'*
    chromaticity diagram.
2011 The Challenge of our Known Knowns (with
  M.R.Pointer)[4]
Lack of tools for known phenomena such as gloss
  and translucency.
2012 The challenge of our Unknown Unknowns
  Lack of knowledge for important topics.

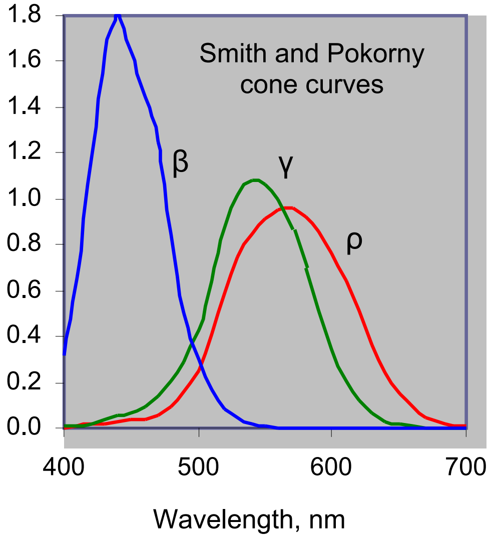

Figure 1*. Cone spectral-sensitivity curves as determined by Smith and Pokorny.*

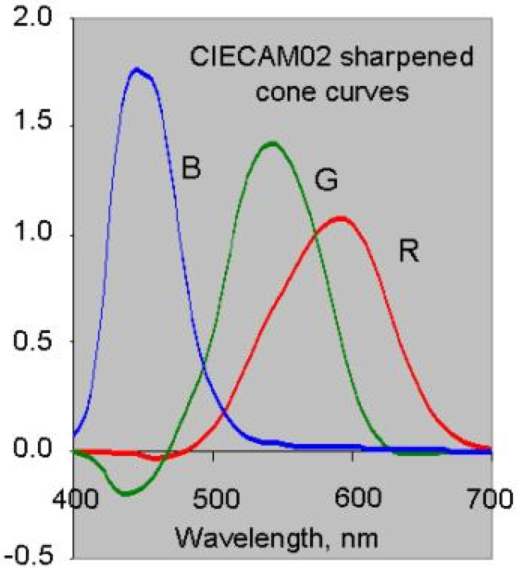

Figure 2. *The spectral sensitivities for the sharpened cone responses used in CIECAM02.*

Sharpened cone responses

Why does sharpening color-matching functions lead to better chromatic adaptation transforms?

Following the earlier work by Lam[5], several more recent investigations have led to chromatic adaptation transforms being based, not on likely cone responses, but on matrixed responses giving sharpened color-matching functions[6,7,8]. The use of these transforms usually results in better predictions of chromatic adaptation, and this type of transformation has been used in the color appearance model CIECAM02[9,10]. It is interesting to ask why such transformations result in better predictions. One implication is that correction for illumination takes place, not in cone space, but rather in a narrowed cone space. But where would this occur? Presumably somewhere between the cones themselves and the cells where color-difference signals are formed.

In Figure 1 are shown the cone spectral-sensitivity curves as determined by Smith and Pokorny[11]; it is clear that the curves for the ρ (Long-wavelength) cones and for the γ (Medium-wavelength) cones overlap considerably and this reduces the effects of chromatic aberration for these cones. In Figure 2 are shown the spectral sensitivities for the sharpened cone responses used in CIECAM02; the reduced R and G overlap would increase color discrimination. Matrices to convert cone responses, $\rho, \gamma, \beta,$ to sharpened responses, $R, G, B,$ have terms of the type shown below.

$$
\begin{aligned}
R &= 1.559\rho - 0.545\gamma - 0.014\beta \\
G &= -0.714\rho + 1.850\gamma - 0.136\beta \\
B &= 0.011\rho + 0.005\gamma + 0.984\beta
\end{aligned}
$$

It is clear that the major components of this matrix increase the difference between the ρ and γ contributions to the sharpened responses.

Why does sharpening colour-matching functions lead to better chromatic adaptation transforms? We don't even know where to look to find out. This is an unknown unknown.

Unique hues

Why are there four unique hues? Why are the unique hues red, green, yellow, and blue? Why do the experimentally determined unique hue loci occur where they do in psychophysical color space?

Of all the characteristics of color perception, the existence the four unique hues, red, green, yellow, and blue, is one of the most striking. That their existence depends on signals derived from differences between cone responses has long been postulated from psychophysical studies, and the existence of such signals in various species has lent support to this view. The fact there appear to be just two color-difference signals, each of which can have two extremes, would lead to there being just four unique hues. Figure 3 shows how signals $\rho - \gamma$ and $\rho + \gamma - 2\beta$ could be formed (where each signal is shown as having either center-surround or surround-center polarity); the formation of an achromatic signal, A, with an average equal to $2\rho + \gamma + (1/20)\beta$ is also shown.

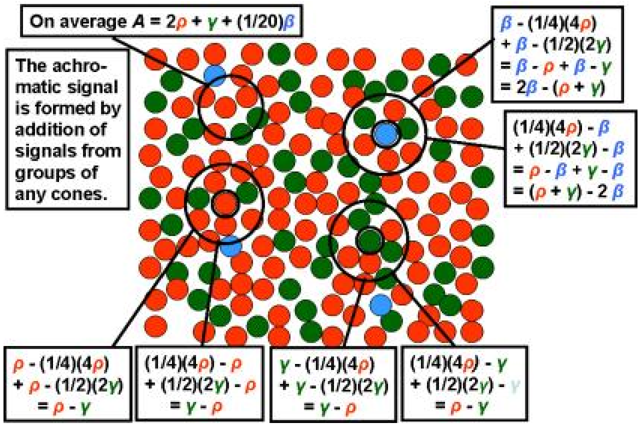

***Figure 3**. Derivation of achromatic and color-difference signals from individual cones.*

One of these two color-difference signals is usually regarded as signifying redness or greenness, and the other either yellowness or blueness. This would result in the four unique hues being red, green, yellow, blue. See Figure 4.

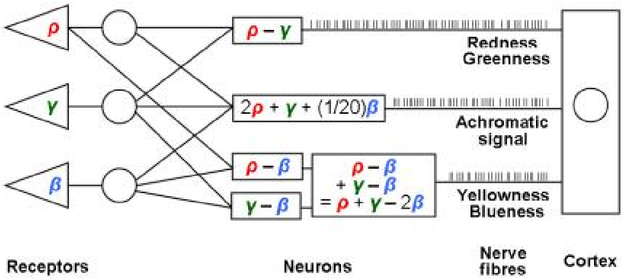

***Figure 4**. Simple representation of the production of achromatic, redness-greenness, and yellowness-blueness signals.*

But what are the reasons for the exact location in color space of the loci of the experimentally determined unique hues? Unique blue is very close in chromaticity to that of typical blue sky[12]. But even if this is the reason for the position of unique blue, there is no similar natural explanation for the loci of the other unique hues.

The curvatures of the unique-hue loci on chromaticity diagrams indicate that the criteria for the unique hues occur after the linear stage of color vision, and hence after the absorption of the light in the cones. The discontinuities of the red-green, and of the yellow-blue, loci at the achromatic point, indicate that the criteria for unique red and unique green are different from one another, and that those for unique yellow and unique blue are also different from one another.

In the CIECAM02 color appearance model, the predictors for hue are based on the unique-hue criteria proposed in an earlier model of color appearance[13]. These criteria are based on the following differences between the cone responses, ρ_a (for the Long-wavelength), γ_a (for the Medium-wavelength), and β_a (for the Short-wavelength) cones (the subscript a indicating signals in the non-linear stage):

Unique red $C_1 = C_2$

Unique green	$C_1 = C_3$
Unique yellow	$C_1 = C_2/11$
Unique blue	$C_1 = C_2/4$

$$\text{where}\quad \begin{aligned} C_1 &= \rho_a - \gamma_a \\ C_2 &= \gamma_a - \beta_a \\ C_3 &= \beta_a - \rho_a \end{aligned}$$

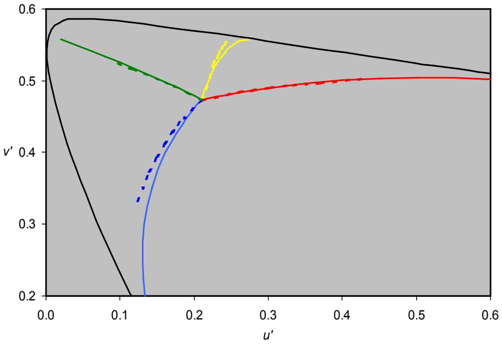

Figure 5. *Unique hue loci: full lines, predictions using Hunt-Pointer-Estevez (HPE) cone curves; broken lines, NCS experimental results.*

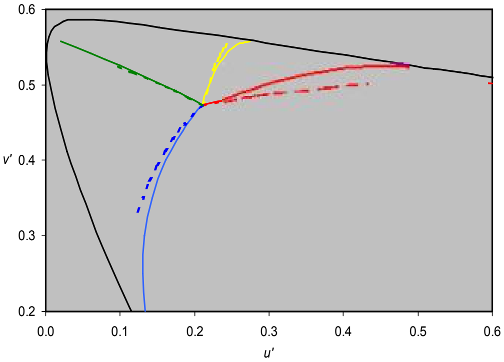

Figure 6. *Same as Figure 5, but using, for the predictions, cone curves approximating those determined by Smith and Pokorny.*

These criteria give very good predictions of the unique hue loci, as shown in Figure 5, but they are based on the Hunt-Pointer-Estevez (HPE) cone spectral-sensitivity curves, of which the ρ curve is more separated from the γ curve, peaking at about 580 nm instead of at about 560 nm, as is the case for the more widely accepted Smith and Pokorny[11] or Stockman and Sharpe[14] curves. The matrix used to derive the HPE cone curves is

$$\begin{aligned} \rho &= 0.38971X + 0.28898Y - 0.07868Z \\ \gamma &= -0.22981X + 1.18340Y + 0.04641Z \\ \beta &= 0.00000X + 0.00000Y + 1.00000Z \end{aligned}$$

The following matrix gives curves that approximate the Smith and Pokorny or Stockman and Sharpe curves more closely:

$$\begin{aligned} \rho &= 0.23X + 0.80Y - 0.03Z \\ \gamma &= -0.55X + 1.45Y + 0.10Z \\ \beta &= 0.00X + 0.00Y + 1.00Z \end{aligned}$$

However, as shown in Figure 6, the simple criterion for unique red no longer gives good prediction of the unique red locus. So is this another indication that some sharpening of the cone responses takes place, in this context, before the unique hues are established, or do the hue criteria in the model not have a physiological basis? These are important unknowns, answers to which call out to be established. The factors 11 and 4 in the predictors for yellow and blue are as yet without a physiological basis.

In CIECAM02, yellowness-blueness, *b*, is determined as the average departure from unique red (for which $C_1 = C_2$) and unique green (for which $C_1 = C_3$).

$$\begin{aligned} b &= (1/2)(C_2 - C_1 + C_1 - C_3)/4.5 \\ &= (1/9)(C_2 - C_3) = (1/9)(\rho_a + \gamma_a - 2\beta_a) \end{aligned}$$

$C_2 - C_1$ is used instead of $C_1 - C_2$ to make yellowness positive as for $C_1 - C_3$. The factor 4.5 (the square-root of 20) allows for the paucity of the β cones (their numbers being regarded as only one twentieth of those of the γ cones). Redness-greenness, *a*, is determined as the departure from unique yellow (for which $C_1 = C_2/11$).

$$a = C_1 - C_2/11 = \rho_a - (12/11)\,\gamma_a + \beta_a/11$$

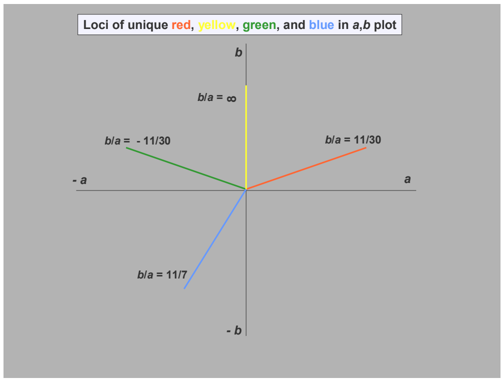

Figure 7. *The unique hues in a plot of yellowness-blueness, b, against redness-greenness, a.*

An average of $C_1 - C_2/11$ and $C_1 - C_2/4$ (the criterion for unique blue) is not used because unique blue is less perceptually distinct than unique yellow. Hue angle is then evaluated as

$$h = \arctan(b/a)$$

The positions of the unique hues in a plot of *b* against *a* are shown in Figure 7.

Because the criteria for the four unique hues are all different, there is a discontinuity as the colour considered passes from one, to a neighbouring, hue quadrant. See figures 8 and 9.

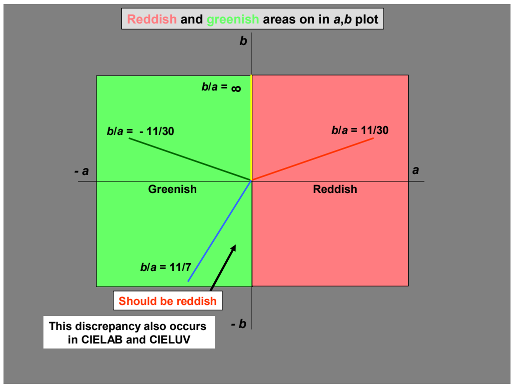

Figure 8. *Discrepancy of reddish hues in the b,a plot.*

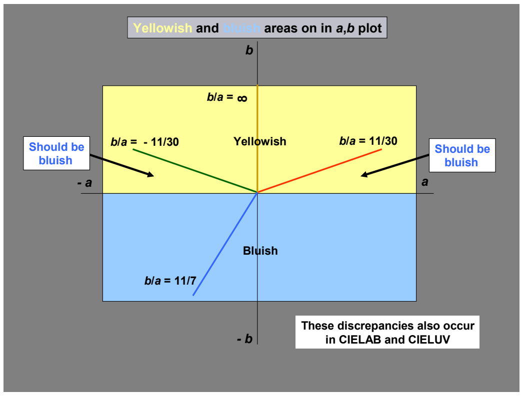

Figure 9. *Discrepancies of bluish hues in the b,a plot.*

The four quadrants are:

Orange (reddish and yellowish), when $C_1 \geq C_2/11$ and $C_2 \geq C_1$
Lime (greenish and yellowish), when $C_1 < C_2/11$ and $C_1 \geq C_3$
Cyan (greenish and bluish), when $C_1 < C_2/4$ and $C_1 < C_3$
Magenta (reddish and bluish), when $C_1 \geq C_2/4$ and $C_2 < C_1$

It would, therefore, be more correct, in future, to have two correlates of redness-greenness, a_y for yellowish colours, and a_b for bluish colours:

$$\begin{aligned} a_y &= (C_1 - C_2/11) = [(\rho_a - \gamma_a) - (\gamma_a - \beta_a)/11] \\ &= [\rho_a - 12\,\gamma_a/11 + \beta_a/11] \\ a_b &= (C_1 - C_2/4) = [(\rho_a - \gamma_a) - (\gamma_a - \beta_a)/4\ ] \\ &= [\rho_a - 5\,\gamma_a/4 + \beta_a/4\ ] \end{aligned}$$

and two for yellowness-blueness, b_r for reddish colours, and b_g for greenish colours:

$$\begin{aligned} b_r &= (C_2 - C_1)/(4.5) = [(\gamma_a - \beta_a) - (\rho_a - \gamma_a)]/(4.5) \\ &= [2\gamma_a - \rho_a - \beta_a]/(4.5) \\ b_g &= (C_1 - C_3)/(4.5) = [(\rho_a - \gamma_a) - (\beta_a - \rho_a)]/(4.5) \\ &= [2\rho_a - \gamma_a - \beta_a]/(4.5) \end{aligned}$$

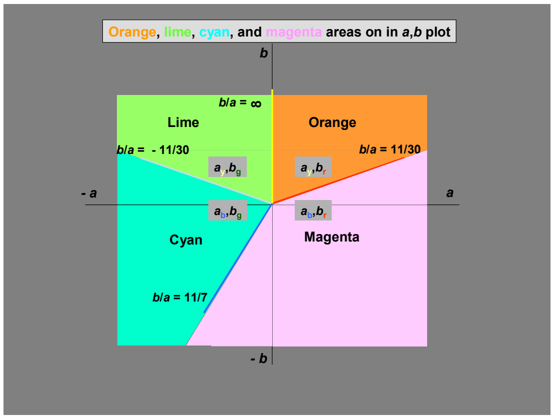

Figure 10. *Correct hue designation in the b,a plot.*

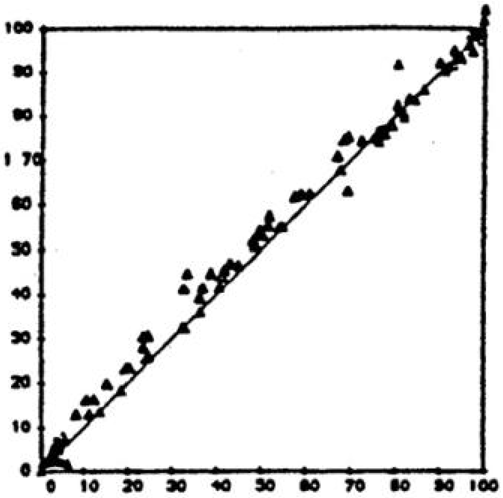

Figure 11. *An example of experimentally scaled hue (y-axis) plotted against predicted hue (x- axis).*

Then, a_y and b_r would be used for orange colours; a_y and b_g for lime colours; a_b and b_g for cyan colours; and a_b and b_r for magenta colours. See Figure 10. These more elaborate correlates of redness-greenness and yellowness-blueness should result in better correlation with experimental determinations of these perceptions; and, when incorporated in the formulas for the correlates of chroma, colourfulness, and saturation, they might also result in improvements in the predictions for these perceptions. The use of a_y, a_b, b_r, and b_g in computing hue-angle would not be expected to make much difference to Hue Quadrature because this measure is anchored at the four unique hues.

The CIECAM02 model provides very satisfactory predictions of hue, as shown in Figure 11. But why do the unique hues occur where they do in colour space? We don't even know where to look to find out. This is another unknown unknown.

Colour-difference formulas

Why do effective color-difference formulas, have to be so complicated?

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It might be thought that an effective color-difference formula could be based simply on the square-root of the sum of the squares of the proportional differences of the responses of the three cone types, ρ, γ, β:

$$\Delta E = [(\Delta\rho/\rho)^2 + (\Delta\gamma/\gamma)^2 + (\Delta\beta/\beta)^2]^{0.5}$$

But this gives poor correlation with observed color differences.

To obtain good correlation, considerable complexity has often been built in to color-difference formulas, as is the case for the CIEDE2000 formula[15]; this formula is entirely empirical with no physiological basis. A more recent formula[16] is based on a modification of the CIECAM02 Color Appearance Space, and has the merit of at least some physiological basis. This modified space, in its form for universal use, is obtained by plotting the following three variables at right-angles to one another:

$$a'_M = M' \cos(h)$$
$$b'_M = M' \sin(h)$$
$$J' = (1.7)J/(1 + 0.007J)$$

where

$$M' = (1/0.0228)\log_{10}(1 + 0.0228M)$$

and M is the correlate of colorfulness, J is the correlate of lightness, and h is the hue-angle, in CIECAM02 .

The colour difference is given by:

$$\Delta E' = (\Delta J'^2 + \Delta a'^2_M + \Delta b'^2_M)^{0.5}$$

In Figures 12 and 13, the performance of this space is compared to that of the CIELAB system. Ideally, all the ellipses should be circular and of the same size; the performance of the formula based on CIECAM02 is clearly better than that based on CIELAB.

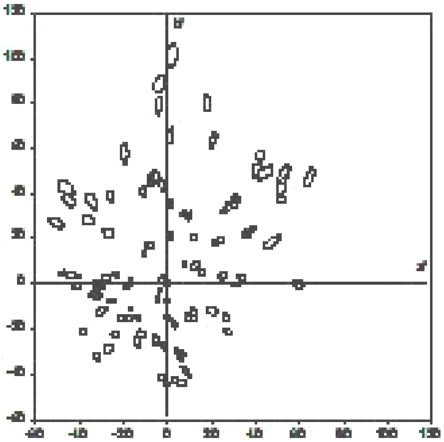

Figure 12. *Experimentally determined ellipses of color differences plotted in the b*,a* diagram of the CIELAB system.*

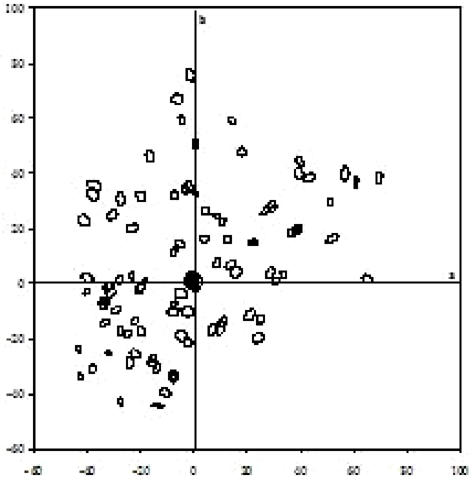

Figure 13. *Experimentally determined ellipses of color differences plotted in the b,a diagram of the space based on CIECAM02.*

Why do effective color difference formulas have to be so complicated? We don't know even know where to look to find out. This is another unknown unknown.

The blueness of whites and blacks

Why do bluer whites look whiter than neutral whites of the same reflectance, and why is this also true of blacks?

When two whites having the same reflectance factor are compared, if one is bluer than the other, it looks whiter. Does this mean that there is something wrong with our $V(\lambda)$ functions? It would seem not to be so. The use of a corrected $V(\lambda)$ function, such as $V_M(\lambda)$ which incorporates the Judd correction[17] does not solve the problem. In the CIE Whiteness Index[18], and in other whiteness formulas, rather than using a different $V(\lambda)$ function, it is found necessary to add a factor that represents increasing whiteness as the chromaticity becomes bluer. In the CIE whiteness formula the whiteness, W, is given by:

$$W = Y + 800(x_p - x) + 1700(y_p - y) \quad \text{or}$$

$$W_{10} = Y_{10} + 800(x_{p,10} - x_{10}) + 1700(y_{p,10} - y_{10})$$

where Y is the Y tristimulus value of the sample, x and y are the x, y chromaticity co-ordinates of the sample, and x_p, y_p are the chromaticity co-ordinates of the perfect reflecting diffuser, all for the CIE 1931 standard colorimetric observer; the subscript 10 indicates similar values for the CIE 1964 supplementary standard colorimetric observer. The higher the value of W or W_{10}, the greater is the indicated whiteness. For the perfect reflecting diffuser W and W_{10} are equal to 100.

It has also been known for many years by launderers that white materials can be made to look whiter by adding a small amount of blue dye; in this case the reflectance factor is actually decreased (unless the additive fluoresces), but the effect is to increase the whiteness.

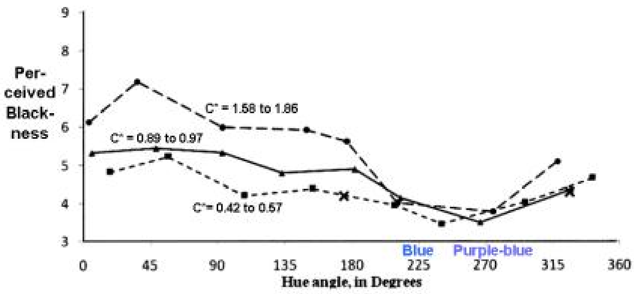

***Figure 14**. Perceived blackness of samples of the same reflectance plotted against hue angle.*

It has also been reported[19,20] that blacks of similar reflectances appear blacker if their chromaticities are in the blue direction. See Figure 14. It has sometimes been suggested that the reason for bluish whites appearing whiter is because, when white materials deteriorate, they usually become yellower; even if this is true for whites, it seems less plausible for blacks. Here is another interesting unknown.

Why does blueness make whites whiter and blacks blacker? We don't know even know where to look to find out. This is another unknown unknown.

Conclusion

Why does sharpening colour-matching functions lead to better chromatic adaptation transforms? Why do the unique hues occur where they do in colour space? Why do effective color-difference formulas have to be so complicated? Why does blueness make whites whiter and blacks blacker? We don't even know where to look to find out. These are unknown unknowns.

Acknowledgements

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Author Biography

Robert Hunt had the privilege of studying color science under W. David Wright at Imperial College, London, after which he was at the Kodak Research Laboratories for 36 years, working on color adaptation, factors affecting color image quality, and devices for making reflection prints. After a period as Assistant Director of Research at Kodak, he has worked as an independent consultant and lecturer on color science and imaging, and has developed color appearance models. He has written two books, The Reproduction of Colour, now in its 6th edition, and Measuring Colour, now in its 4th edition with M.R.Pointer as co-author.

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