The Prime Colors of Human Vision

Their Prescription for Illumination, Color Printing, Color Photography, Color Television, and Visual Clarity

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Introduction

Since before 1700 the notion was abroad among mankind that three particular colors of light have special significance to human vision. For a long time inchoate, the notion gathered some substance by 1800, and identification of the particular colors, as red, green and violet, began to be clear. Then around 1900 both the notion of three particular colors, and the identity of those colors, fell again into obscurity due to the sudden popularity of a competing notion represented by "transformability of primaries." [1] However, in the last 30 years, the validity of transformation of primaries has been questioned, and evidence adduced suggesting such transformation to be inadvisable, if not meaningless. Meanwhile, the three particular colors of light have been identified with considerable precision, and their function in human vision has become clearer. These matters underlie the present paper.

Palmer (1777) attributed trichromacy to "particles of three different kinds" in the retina, rather than to something in the light itself, as did all forerunners. The three kinds of particles respond, Palmer proposed, to three different kinds of light rays, red, yellow and blue. Wunsch (1792) promoted red, green and violet, instead, as best serving to compose all other colors. Young (1802) also proposed three types of retinal particles, each associated with one of the "three principle colours, red, yellow, and blue..." but in 1803 substituted red, green, and violet as the principal colors. Lang writes[2] (1983) "These formulations (of Young's, in the 1803 paper) express very clearly the fundamental difference between his and all earlier trichromatic theories: He did not assume three different kinds of physical rays, but three kinds of sensitive elements in the retina. There is no longer an isomorphism between rays and colors, but an isomorphism between the three kinds of sensitive elements in the retina and the three fundamental color sensations. In other words: The three principal colors do not exist in the outside world of physical radiation, but only in the world of human color sensation. Their existence has its roots in the organization of our visual system...So Young's priority did not lie in his choice of the additive primaries red, green, violet -- here he was anticipated by Wunsch -- nor in the hypothesis of three kinds of sensitive particles in the retina -- this was stated before him by Palmer -- but in the discovery of the fact that trichromacy is uniquely a consequence of the organization of the human visual system."

I wish (1) to transpose Thomas Young's conceptualization from retina to visual system as a whole, (2) to propose isomorphism between the three spectral sensitivities of the normal human visual system and what have been called the three fundamental color sensations, and (3) to stipulate (a) that the "three principal colors" do exist in the outside world of physical radiation, (b) that they are to be identified with the three spectral lights I have termed the prime colors for 30 years (namely, near 450 nm in the blue-violet, near 530 nm in the green, and near 610 nm in the orange-red), (c) that the wavelengths of these three spectral lights mark the maxima of the three independent spectral sensitivities of the normal human visual system, and (d) that it is in those spectral sensitivities that "trichromacy is uniquely a consequence of the organization of the human visual system" (Young). In this context I wish also to review some of the problems in current colorimetry, and to give evidence that (in colorimetry) various shifts toward the prime-color wavelengths and the prime-color construct are alleviating those problems.

Steps in Evolution of the Concept of "Prime Colors"

1. Intersections of the spectral power distributions of visually matching lights: In his "Measurement of Colour", David Wright[3] discussed spectral reflection curves of dyed fabrics which match visually in a certain illumination. He wrote "...their reflection curves are characterized by the common feature that the pairs of curves cross each other at least three times within the visible spectrum. Moreover, each crossing point tends to be located near to the three maxima of the [visual] sensitivity curves..." It follows that, in governing the locations in the visible spectrum of the three required crossing points, the three associated visual sensitivity maxima reveal their spectral whereabouts.[4] In practical cases, the pairs of metameric spectral reflectance curves used by Judd[5] were consistent with intersections near 450 nm, 530 nm, and 610 nm, as were experimental determinations of much later.[6,7]

2. Color Rendering Index: The color rendering index CRI, of white light composed of triads of spectral colors, maximizes sharply (Fig. 1) depending on wavelength of each member of the triad[8]. CRI of white light composed of the optimal triad (roughly 450, 530, 610nm) is more than 80, surprisingly high since the spectrum of that white light is essentially empty.

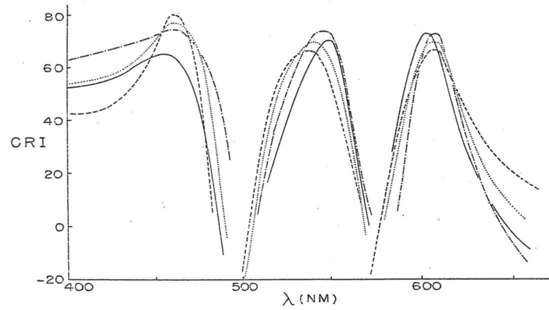

Figure 1. CRI of white light formed of a mixture of three spectral lights, two fixed in wavelength and one variable.

3. Visual efficiency: In white-light mixtures, suppose two of the spectral colors of the above optimal triad are held constant in wavelength, say at 450nm and 610nm, and the wavelength of the third component is varied, keeping color of the white mixture constant. That third component requires maximum total power content in the accompanying pair of spectral lights when the wavelength of the third passes through the remaining optimal value, i.e., about 530nm (Fig. 2)[9] . The inference is that each of the optimal triad is that spectral color to which the visual system responds most strongly, in that wavelength region.

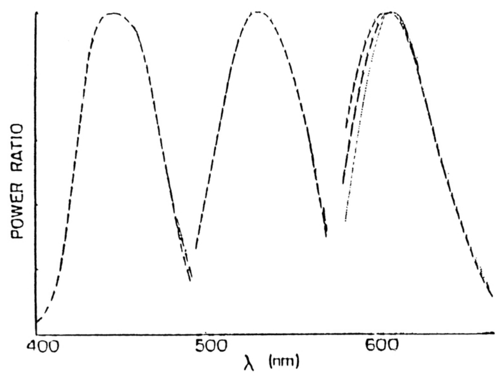

Figure 2. Power in two spectral lights fixed in wavelength per watt in the variable spectral light.

Phenomena 1-3 suggest that the normal human visual system is characterized by three rather sharply defined peak sensitivities at the wavelengths of the optimal triad. This optimal triad of spectral colors, their wavelengths, and the corresponding spectral peaks of the visual system sensitivities, have been termed by the writer the "prime colors" of the normal human visual system.

4. Prime colors of the CIE Standard Observers: By trial and error, the defining functions of one or other of the CIE Standard Observers were transformed, by the writer about 1973[10], to real spectral primaries, such that one real primary coincides exactly in wavelength with the peak of each of the transformed functions. In that case, and only in that case, in the usual series of maximum-saturation color matches by normal human observers, no more than one watt of a primary is ever required to match one watt of any spectral light in the opposing field. Therefore, again, these primaries are the three spectral lights to which the CIE Standard Observer responds most strongly. For this reason, white light illumination, formed mainly of the prime colors, has led to commercial lighting worldwide that is high in brightness per watt expended over unit area.
5. Color Preference: That particular white-light illumination is also high in pleasantness of color rendering. Suppose a series of "daylight color" (6500K) fluorescent lamps is made in such a manner that the prime-color content of the white lamplight is first like that of standard commercial Daylight fluorescent lamplight (low in prime-color content), and then is varied by increasing prime-color content of the lamplight without changing its color. It is seen that pleasantness of coloration (of, for example, identifiable objects such as complexions, foliage, meat, vegetables, fruit, bread) increases sharply and continuously up to lamplight comprised essentially only of the prime-colors[11]. The effect has come to be known, in lighting, as "preferred coloration," with color-preference index CPI as its measure.
6. Prime-color reflectance: In the long run (and it may take a century) peaking the reflectance[12,13] of colored images of identifiable objectsts in the three prime-color regions (Fig. 3) will cause them to appear in "preferred coloration," and at maximum perceived brightness per watt per square meter of illumination.

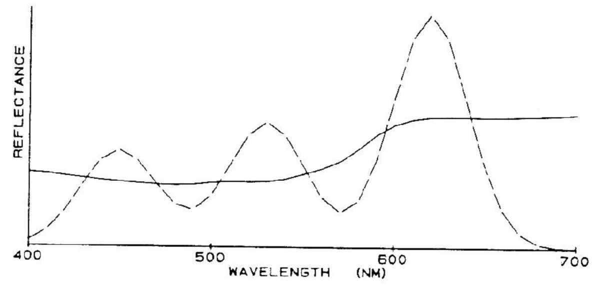

Figure 3. Spectral reflectance of a complexion (solid) and red so as to peak in the prime-color regions.

7. As an aside relating to color photography, during the recent CIE/AIC Conference (June 2001,Rochester NY USA) Robert Hunt mentioned that the red sensitivity of recent color films is approaching the orange-red prime color at about 610 nm (to be followed much later, I suggest, by peak spectral reflectances in the color print).

8. In color television, each of the three components of light emission forming each picture element tend to approach the spectral shape of the three prime colors. In time, those shapes are expected to narrow and to fall increasingly accurately at the prime color wavelengths. The result, forced by the normal human visual system itself, will be maximum perceived brightness of the picture elements per watt content of the emitted light from that element, whatever the source device.[13]
9. Visual clarity. In illuminated areas, particularly those involving seeing considerable distances and much detail in the illuminated scene, the degree of clarity of vision is observed to be markedly in inverse proportion to the measured power in the yellow and blue-green portions of the spectrum, in the spectral power distribution of the illumination.[14]

In summary of the above steps leading to the prime colors, the conceptualization that Thomas Young (and perhaps Wünsch, Palmer and Young), were trying to articulate was perhaps not that red-green-violet would mix to form all colors (which they do not) but that they mark the three different characteristic spectral positions of the three elements of the visual-system sensorium (as Maxwell put it). For two centuries, trichromacy has been recognized as held to by the visual system as a whole. But in that time confusion has reigned because trichromacy has been ascribed to 'something in the front end' of the visual system. Finally, Stiles and Wyszecki[15] wrote that the CIE color-matching data cannot be made to relate satisfactorily to visual pigments in the eye. Their indicated peak sensitivities were more consistent with the visual system sensitivities discussed here, than with retinal characteristics. The one place where trichromacy reliably presides appears to be at the rear end of the visual system, where it, by way of observer judgment, yields the data on which colorimetry is based, and the data on which the human's waking vision depends.

Aristotle wrote (350 BC) "The rainbow has three colors, and these three and no others." [16] He saw this, and was perhaps the first to record the observation, because, outside of the prime-color spectral regions, normal human visual system sensitivity is sharply lower.

Colorimetry and the Prime Colors

Colorimetry should be entirely representative of normal human vision. Otherwise, of course, it fails to substitute for the visual system, and, in particular, fails to yield quantitative measures of what is seen by the visual system. In 1955 Judd published[17] a note entitled "Radical changes in photometry and colorimetry foreshadowed by CIE actions in Zurich," and in 1958[18] commented, speaking of the 1931 CIE Standard Observer, that neither its standard of light nor of color "agree with actual observations."

The urgency brought about by colorimetry failures made itself felt in 1965, when new commercial lamplights (by means of fluorescent lamps) were developed. The guiding objective of the improved lamplights was that their spectral power content be concentrated, so far as possible, at the three prime-color wavelengths, for the reasons implied in the previous Section. That objective resulted in the strong metamerism (difference of spectral composition of two visually matching lights) of which Fig. 4 is representative. In turn, if the CIE functions fail appreciably to conform with those of the normal human visual system, then when the human observer sees a match between the lamplights of Fig. 4, for example, the CIE Standard Observer will not. Strong metamerism of visually matching lights stresses the Standard Observer, in the sense that its functions are severely tested with respect to those of the normal human.

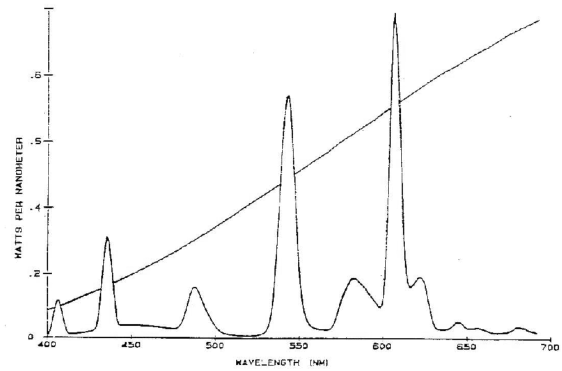

Figure 4. Spectral power distributions of two lamplights, incandescent (smooth) and fluorescent (structured) that visually match (strong metamerism).

The new prime-color lamplights showed marked improvement (a) in usable brightness per lighting watt per unit area, and (b) in pleasantness of coloration. However, CIE colorimetry showed itself unable to evaluate either brightness or chromaticity of the new lamplights, and so it had to be left behind, as these lamplights spread worldwide on their own visually-assessed merits. We in color science are still collectively searching for the three functions that adequately define the normal human visual system. My small working group* has spent thirteen years focused on the elucidation of these problems in colorimetry.[10,19-26] Using our data, I showed[26] in 1998 that CIE-computed chromaticities of white lights, visually identical in both brightness and color to our eight observers, range across deltaEs (color differences) of 50, in CIELAB space. deltaEs of 1 or 2 can, in color matching, be worrisome.

** The group includes such known color scientists as Fred W. Billmeyer, Jr; Hugh S. Fairman; Joy Turner Luke; Danny Rich; Ralph Stanziola.*

I turn now to our first steps[23,24] toward meeting the principal challenge underlying the problems of colorimetry: the identification of three functions necessary to defining a proper colorimetry. I assume that the functions sought are those that are also operative, and definitive of, the normal human visual system. Consistent with the considerations so far mentioned up to this point in the present article, the sought functions are three in number, and peaked near 450 nm in the blue-violet, 530 nm in the green, and 610 nm in the orange-red. Why not, then, simply use CIE functions, transformed to real primaries at these wavelengths? The answer is that such transformation does not improve[20] the capability of a CIE function to mediate a color match; tristimulus errors remain as large as before. As well, the use of an experienced, normal observer, working with his own functions, in his own chromaticity diagram, is of no avail. The trouble is not in the visual color-match data, either those of Guild, Wright, Stiles and Burch, Speranskaya, or in modern data. The trouble lies in the traditional method by which the functions are derived.

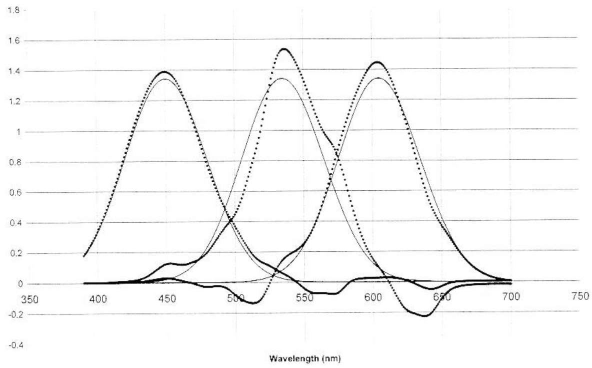

Figure 5. Choice set of three new competent color-matching functions, each with its "starting function".

A new procedure was devised[23] by which the needed functions are extracted directly from pairs[21] of visually-matching but highly metameric white lights. Here, "visually-matching" means "matching by consensus of our eight normal, highly experienced observers." Among the pairs of lights[21] from which the extraction of new functions is made are the most troublesome examples we have found. Among, say, ten pairs of those highly metameric lights, total tristimulus error TTE, committed by a CIE Standard Observer, is reduced by the new functions to 1-2%. Thus the aforementioned ΔEs of 50, in CIELAB space, are reduced to the order of 1. In the extraction procedure, a starting function is chosen, in a form as featureless as possible. The starting function commits an initial TTE of magnitude about that by a CIE function. Over many iterations the error is reduced, by progressively altering the spectral shape of the function. A choice set of three (dotted) functions is shown in Fig. 5, together with their respective (solid) starting functions.

Briefly summarizing these and further aspects of our latest work: Competent color matching functions are extracted directly from visually-matching but strongly metameric pairs of white lights, pairs which stress the CIE functions to definitive failure. Each white light visually matches the same reference 5000K broadband reference white light, in color and brightness. Color matching functions extracted from visual matches made in 1.3-degree* visual fields reduce the total tristimulus error, summed over ten visually-matching pairs, to roughly one percent of that committed by a CIE Standard Observer function. Spectral shape of a new function is simplest when its mean wavelength approximates 450 nm, or 530 nm, or 610 nm, and when its half-width approximates 70 nm. Peripheral shape of the resulting 1.3-degree color diagram, defined by any choice of three of the extracted functions, is also simplest when the characteristics of the choice of three are near those mean wavelengths and half-width. That choice of three functions results in a color diagram (Fig. 6) that is generally similar to the CIE diagram (when it is transformed to real primaries at the prime color wavelengths), and yet differs in four respects: (1) The new 1.3-degree diagram is defined by three functions that make essentially no tristimulus error. That is, each function computes essentially identical tristimulus values for all of the visually matching, strongly metameric white lights. (2) The new diagram shows clustering, in the regions of the prime-color wavelengths, of chromaticities of adjacent spectral lights. This is in accord, for example, with the findings by Wright and Pitt[28] and by Bedford and Wyszecki[29] that wavelength discrimination is most difficult near 460 nm and 530 nm. Such clustering (suggesting visual difficulty with wavelength discrimination) is consistent with our finding that the three independent spectral sensitivities of the normal human visual system peak (their slope passes through zero) in the regions of the prime-color wavelengths. (3) The new diagram shows regions in which the spectrum locus is concave outward, three of the regions being those of the prime-color wavelengths. Finally, the present "best choice" functions are lumpy; that is, they contain components of higher frequency (cycles per nanometer) than are familiar and characteristic of the CIE functions. The presence of such fine structure in functions repre-senting sensitivities of the human visual system has been apparent since Part I10 of this series. The new CMFs are free of influence by the CIE functions, and relate, in origin, neither to traditional color-matching procedures, nor to the presumptions inherent in the derivation of the CIE functions.

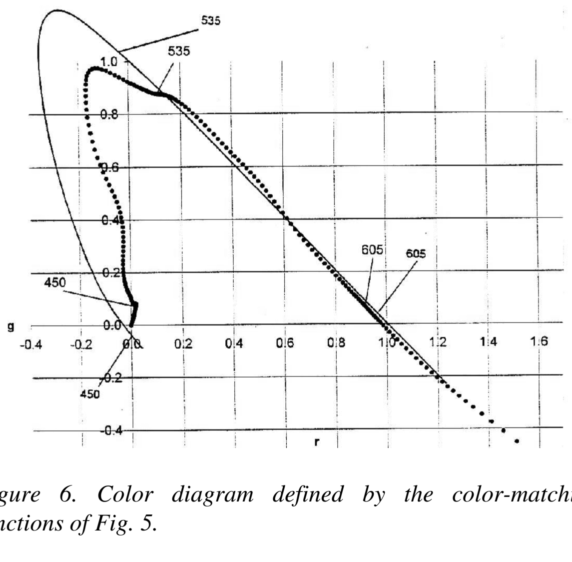

Figure 6. Color diagram defined by the color-matching functions of Fig. 5.

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* *Recommended by Dr. P. Trezona as being a visual field small enough to preclude intrusion into the match by retinal rods; functions appropriate for larger visual fields are suggested in Part VII, to be published.*

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Biography

William A. Thornton received a BS in Physics from the University of Buffalo in 1949 and was Phi Beta Kappa. He received the MS and PhD in Physics from Yale in 1949 and 1951. He was with the GE Research Laboratory to 1956; Westinghouse Lamp Divisions to 1983; and Research-Engineering Consultant. He has 45 patents, 80 articles, Westinghouse' highest honor, the Order of Merit 1978. He received the US National "Inventor of the Year" 1979. He is a Fellow of IESNA, Past Director of ISCC, and President Prime-Color Inc. He lead eight researchers in improving international measurement of light and color.