Four Spectral Channels for Natural Imaging of Scene Colors

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Abstract

Ideal imaging channels should have the same spectral sensitivities of scene recording as vision channels and independently control the primary color sensations of eye. The trichromatic colorimetry is not helpful with its unreal primaries (XYZ) or alternating RGB color matching functions, which are little suggestive of non-negative channel sensitivities. Although the natural color space is formed by two alternating blue-yellow and green-red color axes,[1-3] the non-negative imaging space has to use an independent channel to render each of the four visual half-axes. The short-wave and long-wave channels in 56 modern photographic systems closely simulate their opponency against the yellow and bluish-green vision channels, which are roughly presented with a single middle-wave channel. The channel sensitivities are delimited by the neutral points of rod and cone. The necessary spectral overlaps of non-opponent channels are absent, thus decreasing the saturation of mixed colors. Positive dyes closely simulate the primary blue and red sensations, but the yellow and bluish-green ones are roughly replaced with an averaged yellowish-green color. An accurate rendering of natural saturation, metamery, the problematic bluish-green, purple-red, and low-illumination colors requires division of the middle-wave imaging channel into two separate ones. A spectral specification for the natural four-channel imaging is proposed, basing on the data of physiological, psychological, and medical studies of color vision.

Non-Negative Matching Requires Four Primaries

It is commonly thought that any color is a sum of three basic colors. If real primaries are used, their sums cannot match, however, some colors in principle. In the conventional RGB triad,[4] the significant negative values of $\bar{r}(\lambda)$ denote addition of the red colorimetric primary, R, to a test color itself. The latter *is changed* instead of its actual reproduction with the three primaries. To render it as such, one should add to a positive combination of G and B a fourth, 'minus-R' (blue-green) basic color, complementary to R. A positive trichromatic matching is formally achievable with unreal primaries only, e.g. XYZ, which were especially elaborated for the non-negative description of colors.[4,5]

Unlike the colorimeter, an imaging system cannot use an alternate color space: the real imaging primaries can only summarize. Then there may exist colors in a scene, in particular among saturated ones, which cannot be reproduced with a weighted sum of the primaries. It is useful to remember that almost all the scene hues can be rendered with using *two* imaging channels only.[6] Although the color saturation decreased down to disappearance of some hues, subject to spectral properties of the channels, a 'frequent acceptability of pictures as lovely color photographs' was noted.

Even in the best of three-channel systems, photographic, the saturation and vividness of colors, in particular blue-greens (around 500 nm) and complementary purple-reds, do not suffice for some professional applications.[7,8] No spectral shift of channels improved them without decrease in the saturation of usual basic colors.[8] The technologies aimed to saturate primary colors (e.g., DIR-couplers in the color photography) worsen mixed colors.[8] Even if the mean color saturation is equal to that in the scene, it does not satisfy consumers,[9] suggesting a too low saturation of important mixed colors.[2,8] The three-channel imaging lacks in the identical rendering of metameric colors:[2,5,10] short-band hues usually differ in images from their wide-band analogues. It fails also in realistic rendering of colors of low-illuminated scenes.[7,11] Some color negative films already involve an auxiliary spectral channel around the 520-nm minimum of $\bar{r}(\lambda)$.[7, 8,11]

The three-channel systems take the opportunity of acceptable imaging following from the fact that such psychologically dominant colors as that of face skin lie within the positive matching space of typical imaging primaries. Perfectly rendered flesh tones lead to high quality judgments of an image as a whole.[12] The lightness, sharpness, and graininess quality of face image act in a similar way:[13] even a strong deterioration of background details is not perceived by mass consumer in an image context.

The Triad of Cones and Anything Fourth?

'How Thomas Young would have smiled if he had realized the endless controversy to which his suggestion would lead!' wrote Write already fifty years ago.[14] All the subsequent efforts unambiguously to prove the reality of short-wave (S), middle-wave (M), and long-wave sensitive (L) cones rather contributed to the controversy than clarified it.[4] No anatomical differences among human photoreceptor cells have ever been observed, except for those between the rods and the cones. In vertebrate retinas, no stable visual pigment

was chemically isolated, except for rhodopsin from the rods and iodopsin from the cones.[5]

Electrical potential responses recorded from single light-sensitive outer segments, OS, of the photoreceptor cells *at a low illumination* demonstrated with confidence the rhodopsin sensitivity (maximum at ~500 nm) in the rods[15] and the iodopsin sensitivity (around 560 nm) in the L-cones.[16] The M-cone curve published seems to be an artifact. It was recorded from only one photoreceptor cell and had the same spectral maximum as the L-cones. No S-cone was found at all. There was no spectral sensitivity curve recorded with maximum over 560 nm, thus leaving without explanation the 610-nm sensitivity hump of the foveal vision.[14]

The differential spectral reflection of living retinas cannot be explained in the terms of spectral sensitivity and light absorption of three cones. It suggests photoproducts accumulated within photoreceptor cells at photopic illumination.[17] The lifetimes of the usually photosensitive[18] intermediates are minutes at physiological conditions.[19] Their significant presence '*in vivo* suggests a functional role, since otherwise their formation would operationally interfere with biochemical regeneration of rhodopsin'. Chromatography, capable of additional stabilizing of chemical intermediates, has detected the extra pigments in illuminated retinal suspensions.[5]

Most of the curves of cone spectral absorption were close to that of iodopsin (~560 nm).[20,21] The rare 'S-cones', which had the 420-460 nm absorption maximum, were mainly found[20] until after-surgery keeping was significantly improved.[21,22] The poorly reproducible curves could be assigned[18] to some products of non-photochemical decay of visual pigments. The portion of 'M-cones' (530-nm absorption maximum) in the retinas studied is seen substantially to grow with the intensity of surgical illumination.[21] A long-living photochemical intermediate of iodopsin was long ago suggested to respond for the spectral absorption curves: '...the green sensitive pigment... could itself be a product of the bleaching of the red sensitive pigment'.[18] The main procedure used then could not in fact evidence pro or contra the suggestion. The apparent bleaching of the green pigment with light from the sensitivity range of red pigment implies that the thermally decayed mass of green pigment is larger than the photochemically decayed mass of red pigment per a successive cycle of illumination and darkness.

The several distribution peaks of L-cones and the doubled scatter of M-cone maxima may indicate two-pigment mixtures. 15% cells 'were rejected from precise computations of absorbance spectra', which had been expected always to fit a single-pigment template.[21,23] The spectral absorption of single cones frequently looked consisting of spectral components corresponding to two different pigments.[24,25] The averaged spectral absorbtion of M-cones[21] demonstrates an extra hump at the iodopsin absorption maximum.

When molecular genetics variations in color deficients were *a priory* treated as 'photopigment genes',[26] they could not give independent evidence for the three cones. Biochemically produced at poorly defined illumination,[27,28] pigments, other than rhodopsin and iodopsin, can be the intermediates. Syntheses, performed with using a normal or deuteranopic genetic material, gave the 'L-cone' and 'M-cone' pigments. No successful synthesis is known that would have produced the 'M-cone' pigment with using the genes of protanope who is assumed to have the M-cones but no L-cones.[5,27]

The opponent basis of color vision appears to be already a common knowledge in physiological, psychological, and medical studies.[5] The potential responses of alternate sign within two or three opponent spectral regions were first recorded from single photoreceptor cells[29] after a strong illumination of retinas.[30] They were later detected in other layers of retina along the neural pathways and explained by interactions between the three cones, which can differentiate three spectral regions only.[5] For instance, the green-red opponency was assumed to result from the difference of M-cone and L-cone responses. A tritanope is supposed to have no S-cones since disposes of only two complementary blue-green and red sensations as the subjects with an eye normal report.[31,32] The sensations and their mixtures are blue-green (495 nm) or red (650 nm) of various saturation, or white (gray) like that seen at the 460-nm and 575-nm neutral points or under normal white illumination.[31,33] A normal central fovea that contains *no rods* produces the tritanopic sensations only.[34]

They assume the blue-yellow opponency to result from interaction of S-cone response with the sum of M-cone and L-cone responses although no yellow sensation can be produced by the M- and L-cones in the normal central fovea or tritanopic retina. A protanope and deuteranope supposedly have no L- or M-cones, respectively. They possess the only two *complementary* blue (460 nm) and yellow (575 nm) sensations as the unilaterally dichromatic subjects report.[31,32] Both the green and red sensations are absent although elimination of red component from a neutral sensation necessarily leads to a blue-green sensation, and vice versa, in the normal or tritanopic colorimetry. A normal retinal external periphery, which contains *only the rods*, produce the same opponent blue and yellow sensations.[34] A kind of protanopes was proved to have *neither L- nor M-cones* but to possess the blue and yellow primary opponent sensations.[35]

The rods whose responses saturate only at high light intensities[36,37] 'may continue to function over a greater range of intensities than is generally accepted'.[38] The Purkinje shift, frequently considered as a consecutive transition from the scotopic rod vision to the cone vision, requires 'surprisingly high intensities before the photopic curve was approached.' The shift, deduced by some authors[39] from the photochemical accumulation of rhodopsin intermediates within the rod, is practically absent in tritanope who also has no blue-yellow sensations, and in some of rod-monochromates.[38] At photopic conditions, the residual activity of rods may 'constitute the basis for the blue mechanism'[34,40] and participate in producing the blue and yellow sensations.[37]

The Blue-Yellow Opponent Receptors in the Rod and the Green-Red Ones in the Cone

An intra-receptor optical mechanism of opponent color separation was recently proposed[1,41] to avoid the inconsistencies. The light-sensitive OS in the rod or cone is known to consist of two successive parts along the light path that differ in their growth mechanism, structure, and electrical contact to the cell membrane.[42-44] 'In the basal *third* of cone outer segments and in the basal *twentieth* of rod outer segments, the membrane of the <light-sensitive> sacs was frequently seen to be continuous with the cell membrane, but the points of continuance fell off sharply above these levels... The continuities may have functional significance in regard to signal transmission...'[42]

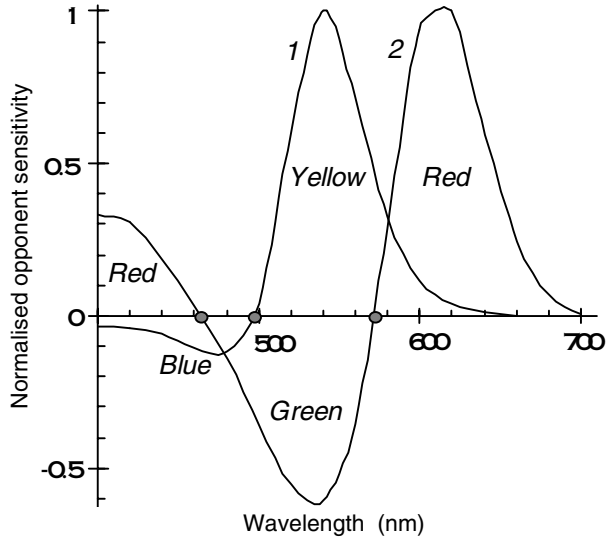

Figure 1. Normalized differences of spectral sensitivities of the distal and basal parts in the rod (1) and cone (2) outer segments at photopic illumination. Gray circles denote the neutral points.[2]

Mathematical simulation demonstrated[1] that the human color vision consists of two dichromatic opponencies: an iodopsin-based green-red one in the cone and another rhodopsin-based blue-yellow in the rod (Fig. 1). They do not occur until long-living colored intermediates[17,19] of visual pigment accumulate enough at photopic illumination. In achromatic states of the rod and cone (also in the retinas of rod- and cone-monochromates[5]), their spectral sensitivities are close to those of rhodopsin and iodopsin, respectively. In the photopic chromatic states, the spectral sensitivity of rod is shifted to 530 nm and that of cone to 610 nm.[1]

The difference of the photopic spectral sensitivities of basal and distal parts in the rod OS (Fig.1, curve 1) changes its sign, which induces the blue or yellow primary sensations, at the neutral point of protanope (~495 nm). The difference in the cone OS (curve 2) divides the visible spectrum at the neutral points of tritanope (575 and 460 nm) into two regions of red and one region of blue-green sensation. The two differential receptors in the rod and two in the cone produce the *four primary color sensations* within the *four independent regions* of subject spectrum where their saturation varies from zero in the neutral points to a maximum value.

The normalized curves depend on the length ratio of basal and distal parts and do not vary with the total length or diameter of OS. Up to 20% shedding of distal part in the course of its periodical renewal[43] in the retina, and orders of magnitude variations in photopic content of rhodopsin in the rod and the iodopsin in the cone also have practically no effect.[1] The invariance on a relative scale leads to the practically invariant chromatic responses as the electrical potential of a photoreceptor cell[45] is a logarithmic function of light intensity in the photopic range where the noise term becomes negligible.

An alternate color matching and characterization in colorimetry can use only two of the non-opponent vision primaries each including its opponent 'minus-state'. A perfect imaging system should simulate the four spectral receptors of vision and their primary color sensations, which are seen unmixed even if may not be of maximum saturation at the 460 (blue), 495 (blue-green), and 575-nm (yellow) wavelengths of neutral points, as well as over 650-nm (red) longwave sensitivity limit of the rod.

An accurate rendition of all the colors of a scene requires that every image detail would have a spectral absorption which would affect each of the four vision receptors like a respective scene detail. That cannot be achieved without using a fourth channel. An ideal system should record four spectral ranges of every subject like the four differential vision receptors did, and separately represent them with the four respective simulations of primary color sensations.[2]

In an *additive* system to form a self-luminous image on an electronic display (PC, TV, consumer video), in color holography or additive photography and cinematography:

(1) Each positive image should give rise to a primary hue sensation with using a monochrome radiation (around 460, 495, 575, and 650 nm) or a broad-band filter whose spectral transmittance is maximum in the vicinity of one of the wavelengths. The blue and yellow radiations, as well as the blue-green and red radiations summarized should produce achromatic sensations.

(2) Each positive image should be pictured with the spectral sensitivity of recording channel that simulates the differential sensitivity of respective color vision channel. The spectral regions of an opponent pair of channels must not overlap. Those of a non-opponent pair should overlap like in a respective pair of vision channels, one of the rod and another of the cone. The channel to control the red sensation has to possess an extra sensitivity range in the shortwave region of the visible spectrum (Fig. 1).

In a *subtractive* system (digital printing, photography, reprography, or polygraphy):

(1) A positive dye should give rise to a primary sensation of vision. Their maximal absorption has to lie around 460 (yellow), 495 (red), 575 (blue), and 650 nm (blue-green).

(2) The equivalent optical densities of all the dyes should give rise together to a gray sensation. If a dye is absent, the remaining dyes must produce its complementary primary. Their absorption minimum should be close to the wavelength of absorption maximum of absent dye, thus maintaining the primary hue at various densities of positive dye.

(3) The spectral sensitivities of recording channels should simulate the differential sensitivity ranges of the distal and basal partial receptors in the rod and cone and independently control the respective subtractive dyes. They must not overlap within an opponent pair but should do in a non-opponent pair of the imaging channels.

The Three-Channel Approximation

The three-channel imaging often appears satisfactory because of the extensive photometric tolerances for rendering all of the scene details, except for such psychological or psychophysical dominants as flesh tones or diffuse-white scene fields.[12,13] In the absence of fourth imaging channel, the three channels are generally re-adjusted so that the critical colors would be rendered most realistically. Everybody knows the feeling of perceptual dissatisfaction with recently pictured images when other scene colors still remain in one's memory. The distortions are especially annoying if the colors are specifically important for a consumer, e.g., dress colors in a woman portrait, or if an image can be directly compared with the original scene:[12] in the video or digital photography with instant images, or in the art reproduction.[7]

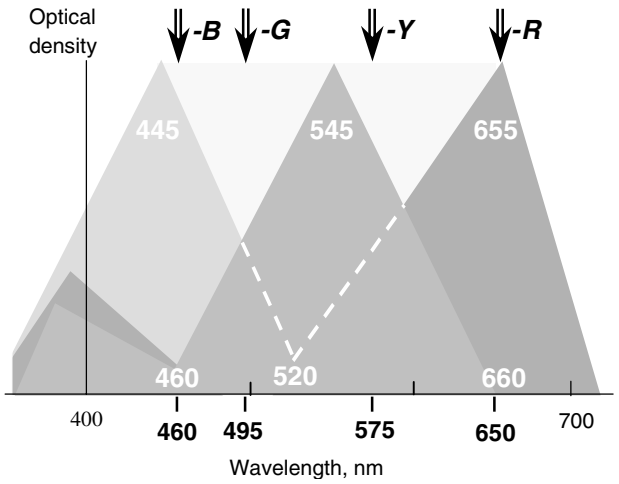

Figure 2. A schema of spectral absorption of the three positive dyes in the modern color photographic papers and reversal films

The spectral properties of the three common channels in the modern imaging tend indeed to approximate as well as possible the four vision channels above. In the color photography, they were selected for over a century of technological development and mass practical testing. The absorption maxima of positive dyes have been found to lie within ± 10 nm around the wavelengths of 445, 545 and 655 nm in 27 modern photographic papers and reversal films produced by Agfa Gevaert, Kodak, Konika, and Fujifilm (Fig. 2). The first and third maxima, as well as the respective two-dyes minima (around 460 and 660 nm) are close to the respective primaries of vision (~460 and 650 nm).

A 495-nm dye independently to control the blue-green vision primary (and complementary red color) is absent. The primary is averaged with the 575-nm yellow primary into the yellowish-green 520-nm sensation and 545-nm 'minus-primary'. Their complementary correspondence remains unsatisfactory even in the best imaging systems. The inaccuracy can, however, partially compensate the absence of the two separate blue-green and yellow primaries. The light-green subject colors are rendered bluish and dark-green colors are yellowish in an image.

The spectral sensitivity ranges of the blue-, yellowish-green- and red-controlling channels of 46 modern negative and reversal films do not practically overlap each other. The channel sensitivities abruptly decrease down to 10% their maximum value in the vicinity of 495-nm and 575-nm neutral points of the rod and cone, as well as at the 650-nm sensitivity limit of rod (Fig. 3) with maximal deviations within ± 15 nm. The spectral region of blue imaging channel simulates the respective vision channel. The spectral regions of the yellowish-green and red imaging channels together perfectly simulate the yellow vision channel (495 to 650 nm).

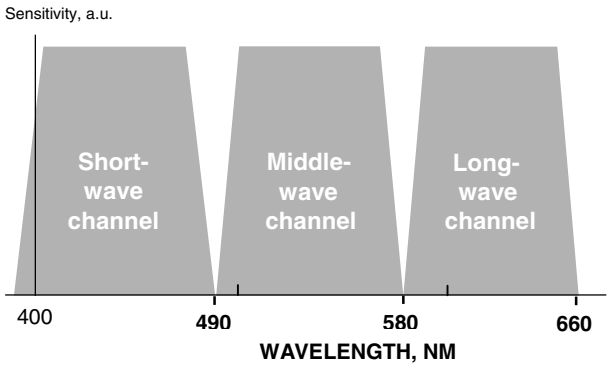

Figure 3. A schema of sensitivity ranges of the three spectral channels in modern color negative and reversal photographic films

Two vision channels are represented in part. The red imaging channel is confined to the 575-nm neutral point and the 650-nm sensitivity limit of the yellow vision channel. It lacks in the long-wave (over 660 nm) and short-wave (under 460 nm) ranges of the red vision channel. The green imaging channel is also a hybridized simulation of the blue-green vision channel with the yellow channel. Its sensitivity limits at 490 ± 10 and 580 ± 15 nm are forced to simulate their sensitivity separation from the respective opponent blue and red vision channels. It lacks partly in the sensitivity range of green vision channel between 460 and 495 nm.

In the absence of fourth channel, the necessary overlaps of spectral sensitivities of red and blue-green channels with non-opponent channels cannot be provided. They can play a crucial role in rendering the saturated color mixtures and the problematic[2,7,8] blue-green or purple-red hues. The spectral

sensitivities of differential vision channels (Fig. 1) have been calculated basing on the data whose accuracy[19-25] may need refining to meet the requirements of color imaging.

Conclusion

1. The usual three-channel imaging is an approximate simulation of the four spectral channels of color vision. No triad of real primaries can match all of the scene colors as their sum only. In imaging, one cannot 'subtract' a primary by adding it to a 'test color' itself.
2. Natural, high-fidelity imaging needs four channels to simulate the spectral sensitivities and primary sensations of the differential opponent color receptors: the blue-yellow pair in the rod and green-red pair in the cone.
3. The four-channel imaging should increase color saturation to its natural level even for the 'difficult-to-create' blue-green and purple-red hues, as well as correctly render metameric and low-illumination colors.

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Biography

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