The history of spectral sensitivity functions for humans and imagers: 1861 to 2004

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ABSTRACT

The spectral response of color systems isolates long-wave information about the world into its long-wave channel; as well the system isolates middle- and short-wave information into their channels. Crosstalk is the dilution of primary channel information with unwanted information from other channels (long-wave channel response to middle- and short-wave information, etc.). Even though Maxwell invented both 3-color photography and the color matching functions of human vision, these fields have standardized on entirely different classes of sensitivity functions. Image Makers use narrow band, minimally overlapping, sensitivities to minimize crosstalk between the color information found in different spectral regions. Human vision, limited by the photochemistry of visual pigments, uses sensitivities with considerable spectral overlap at the early receptor level and employs post-receptor processing to achieve remarkable properties not usually found in image reproduction. The specific properties of spectral crosstalk provide an important signature of how humans achieve color constancy.

1. INTRODUCTION

Four distinct scientific disciplines have contributed to our understanding of human vision's and color imagers' sensitivity to wavelengths between 400 and 700 nm: Physics, Physiology, Psychophysics and the practical Engineering of Image Making. Humans have made colored images for many centuries in all cultures. In 1720 LeBlon[1] developed a technique of color printing using three different color-separation printing plates. LeBlon inspected the image to be printed and hand engraved the three plates to achieve the desired colors. In 1801, the time of Thomas Young's historic Bakerian lecture[2] proposing that the number of types of color receptors in the retina was limited to three, Image Makers were very highly skilled in producing high volume, economical color images. The technique used black and white printing to supply the image and high-spatial frequency information and hand-painted watercolors for hue. One idea that differentiated Image Makers was that they had little choice but to work with complex images. Physics, Physiology and Psychophysics, at first, studied the color properties of a single pixel.

1.1 How Color Theories Use Spectral Information

At the risk of major oversimplification, there are three approaches to understanding color. First, in the Newton-Young-Maxwell tradition (1704 to ~1870), the relative quanta-catch of human color receptors was thought to determined color.[3] The spectral response to light, as sampled by three types of cone sensors, was all that was needed to explain color appearance.

Second, the late 1800s saw a revolt against the over-simplistic Psychophysics of Wundt and Weber. For example, experiments on color constancy demonstrated that the appearance of objects is constant in illuminants with very different spectral content. Helmholtz suggested "unconscious inference" which calculates the color of the illuminant, so as to subtract it out of the quanta-catch information of the retinal receptors. Von Kries suggested that changes in spectral illumination caused changes in receptor sensitivities (called adaptation) as the mechanism of constancy.[4]

Third, the 1960s saw the start of three major bodies of work establishing that multiple, independent channels of spatial comparisons control human vision. Hubel and Wiesel's neurophysiology of the visual cortex[5], Fergus Campbell's psychophysics of spatial-frequency channels,[6] and Edwin Land's Retinex theory[7] of color all established that vision works by spatial comparisons. Physiology and Psychophysics then had to embrace the complex image, as Image Makers had done for centuries. Retinex uses spatial comparisons within a color channel to establish relationships across the entire image, and then compares the three color channels to generate color appearance. Here relative quanta catch within a channel is more important than absolute quanta catch at a pixel.

2. HISTORY OF COLOR SENSITIVITY FUNCTIONS

There are hundreds of different three-channel color sensitivity functions. They fall into two distinct groups: narrow, minimally-overlapping curves used by Image Makers; and broad, overlapping curves derived from characterizing human vision. J. C. Maxwell described both in the 1860s[8]. He was the first photographic color Image Maker. Although the experiment is famous and it is the foundation of all color photography, it was technically flawed. Ralph Evans, in a Scientific American article on the 100th anniversary of the Royal Institution demonstration, pointed out that the records were most likely responding to the ultraviolet reflectances of the colored ribbon.[9]

As well, Maxwell wrote the first color matching equations from matches made using a spinning disc. His human sensitivity functions were derived from monochromator color matching data. The curves shown in Figure 1 are the predecessor of all CIE colorimetric standards.

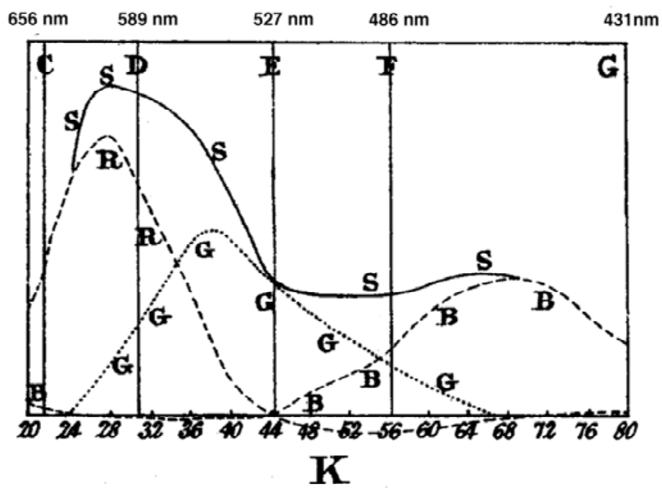

Figure 1 plots Maxwell's sensitivity functions for R, G, and B sensitivities for observer K. Observe that these curves are very broad and show significant spectral overlap. This is in contrast to the narrow-band filters used by Thomas Sutton who made the color separation photographs used by Maxwell in his 1861 Royal Institution Discourse[9]. Note that Maxwell's K is calibrated using the Fraunhofer spectral lines.

Since all visible wavelengths can be matched by three appropriate wavelengths, it is assumed that three types of cone receptors report information about three independent spectral channels. Let us segment the wavelength spectrum into three segments: a red-making or long-wave segment above 590 nm; a green-making or middle-wave segment between 490-590 nm and a blue-making or short-wave segment below 490 nm.

Maxwell's R sensitivity function has the greatest response to long-wave light (Fraunhofer C to D, >590 nm). G has the greatest response to middle-wave light (Fraunhofer D to F, 590 to 490nm). B sensitivity function has the greatest response to short-wave light (Fraunhofer F-G, <490 nm). These are the primary responses. In addition there are significant crosstalk responses. The B sensitivity responds to middle-wave information and the G sensitivity responds to long- and short-wave information; the R sensitivity responds to middle- and short-wave information.

2.1 Film sensitivity functions

In 1889 Frederick Ives tried to combine Maxwell's two ideas. He proposed that color separations, used to make color reproductions, would have the most "natural color" if the separations had the same spectral sensitivities as humans. He published a book and filed a US patent.[10] As described by Friedman, the pre-eminent historian of color photography, *"The Ives disclosure let loose a rather lengthy discussion from which very little seems to have resulted. The poor results that were obtained when using filters for color separation whose transmissions corresponded to color-mixture curves, soon forced the subjective idea of color reproduction into the discard, and the further development of the subject of color photography appears to have proceeded along objective lines."* [11]

Despite a significant investment in the idea of using broad sensitivity functions, Ives abandoned the idea and used narrow-band filters in his 1895 commercial Kromstop color cameras.

Spenser describes a clever devise used to measure film sensitivity to wavelength called a wedge spectrometer.[12] This instrument was an extremely efficient means of plotting a film's sensitivity vs. wavelength function. It combined a spectrum made with a white light and a prism with a linear transparent photographic gradient. The gradient had variable transmission along one axis of the plate and constant transmission in other. The two were combined so that wavelength varied along the horizontal direction and transmission along the vertical. By placing a light-sensitive film on the plate, turning on the light for the correct exposure and developing the image, the operator had a plot of the film's sensitivity function (Figure 2).

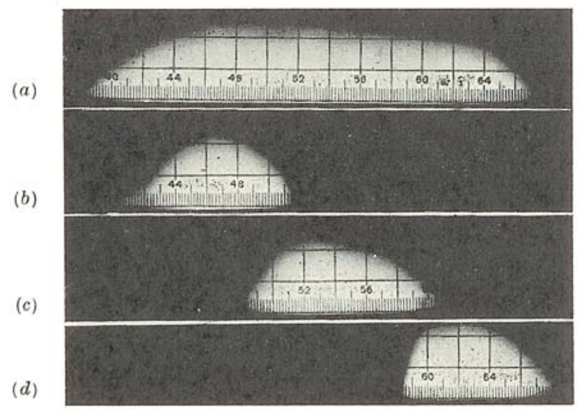

Figure 2 show a plot film sensitivity made by a Wedge Spectrogram. Top (a) shows a typical panchromatic emulsion mage by daylight; (b), (c), (d) show the same emulsion exposed through typical Tricolor Blue, Green and Red Filters respectively.

R. W. G Hunt describes the sensitivity of typical films in Figure 3.

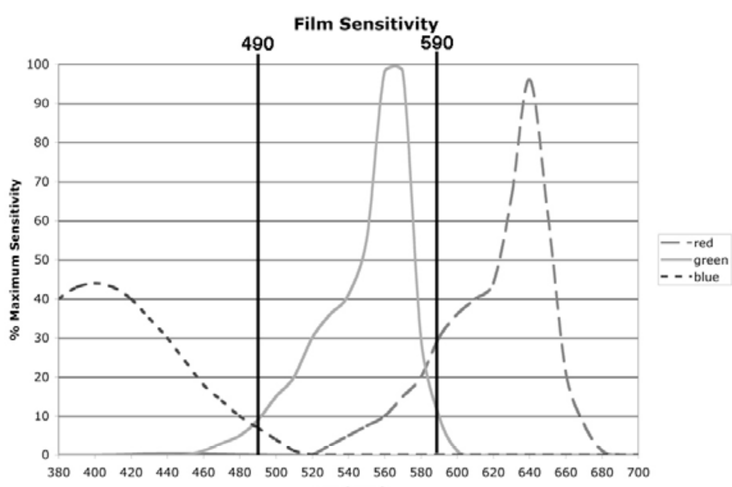

Figure 3 is the spectral sensitivity of a typical film (redrawn from Hunt[13]). It is representative of almost all film and electronic camera sensitivity functions.

Voglesong divides the visible spectrum into three regions in Figure 4. This response is derived from measurements of standard instruments over three decades and extrapolations to optimize spectral separation.[14] All photographic, printing and display technologies observe the general rules described here.

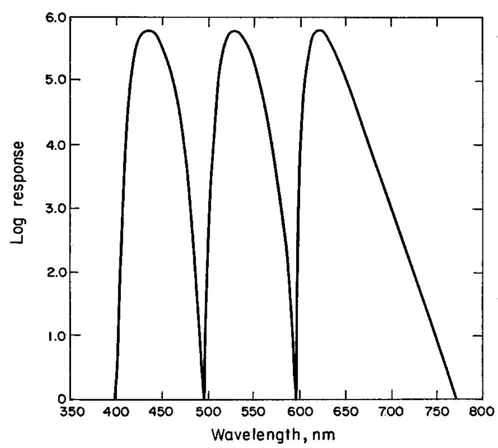

Figure 4 shows Voglesong's curves for the ideal spectral response for Status A densitometry. The troughs between sensitivity functions are at 490 and 590 nm.

Color Image Makers clearly reject the ideas of Ives's "natural color" sensitivity functions. Their primary goal is the minimization of spectral channel cross talk. This is in sharp contrast with Maxwell's human sensitivity functions and its descendants.

2.2 CIE Colorimetry

Maxwell was the first to generate color-matching functions. He was followed by Konig, Dieterichi, Abney, Wright and Guild all generating similar functions[15]. Wright and Guild's data became the basis of the 1931 CIE international colorimetry standard that is most commonly used today to describe color matching. In 1964 a newer 10° color matching standard was adopted by CIE. They 2° and 10° standards differ in their green and blue sensitivities (See Stiles and Wyszecki for details[16]).

Figure 5 is the plot of CIE X, Y Z sensitivity functions. Compared to Maxwell, we see a more prominent secondary absorption of the X sensitivity function below 500 nm. Otherwise, these curves have the same general properties associated with very broad spectral sensitivity functions and considerable crosstalk between color channels.

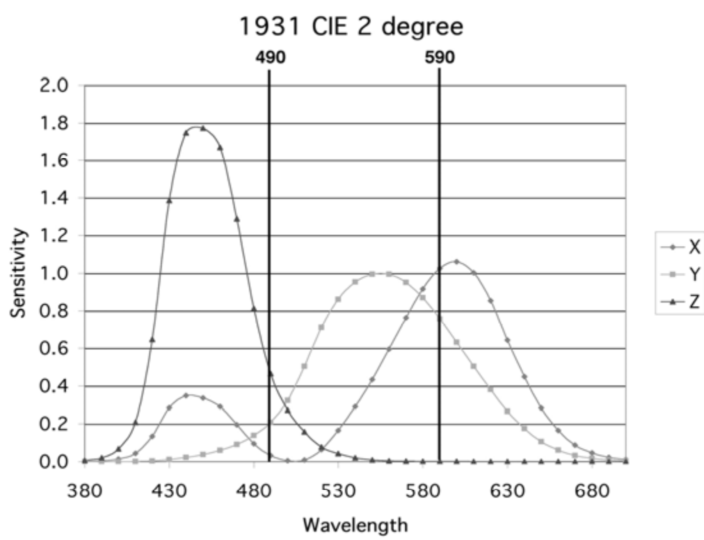

Figure 5 is a plot of CIE 1931 X, Y, Z Color Matching Functions. Peak sensitivities are: Z= 450, Y = 555 X = 610 and 440 nm.

2.3 Visual Pigment Sensitivities

All visual pigments, in all animals, share the same chemistry. The light sensitive molecules in all rods and cones have two components: retinal and opsin. Retinal is the chomophore that combines with the protein opsin. Dartnall observed that visual pigments have the same shape when plotted on a wave number axis.[17] In 1955, Wald, Brown, and Smith's[18] classic paper on visual pigments described experiments on Iodopsin using extracted visual pigments (Figure 6). The advantage of extracted pigment measurements is that the concentration of pigments is high enough to measure spectral sensitivity over the entire spectrum. Extracted pigment data is best for determining the shape of sensitivity functions. Single cell measurements are best for measuring the peaks of sensitivity functions.

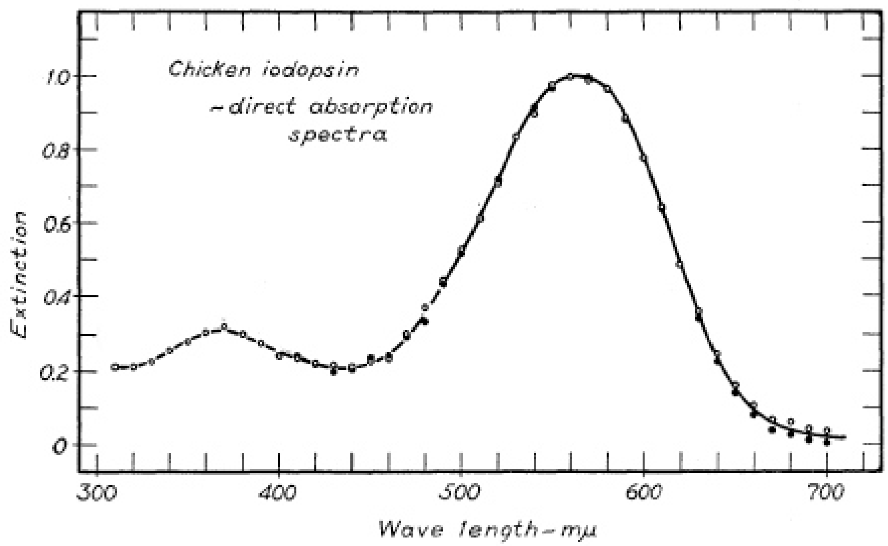

Figure 6 plots the absorption spectra of iodopsin, a visual pigment. With a peak sensitivity at 562, a trough at 435 and a secondary ultraviolet sensitivity peak at 370 nm (From Wald, Brown and Smith).

In 1964, in adjacent issues of Science, Marks, Dobelle and MacNickol[19] and Brown and Wald[20] published their measurements of the actual sensitivity in cone outer segments. Using very high magnification light microscopy they measured the transmission of light through cone outer segments. The cones, excised from human retinas, were dark adapted. They measured the spectral transmission of the cones in the dark-adapted retina. They then bleached the light sensitive pigments with white light and measured the transmission of the segment. The difference was the absorption spectra of the cones with peaks at 565, 540 and 440 nm. More recent data from Dartnall, Bowmaker and Mollon[21] (1983) and have shown similar results with peaks at somewhat shorter wavelengths (Figure 7). The cone sensitivity functions have broad overlapping curves. The peak of the short-wave pigment 420-440 is a little shorter than the CIE Z peak 450, the peak of the middle-wave is at 530-540 less than 555 of Y and the peak of the long-wave function is 560-565 much shorter than the 610 nm peak of X. Nevertheless Smith and Pokorny showed the psychophysical CIE and the physiologic cone functions were consistent transforms of each other when pre-retinal absorptions are included. Color matching experiments provide consistent sets of sensitivity functions. They do not provide a unique triplet of sensitivity functions.

Human sensitivity functions are both similar and different from color matching functions. They both have broad overlapping sensitivities. Yet, cone sensitivities are much broader and have peaks at much lower wavelengths. Cone sensitivities represent the actual light absorption of light at the receptors. As David Wright often pointed out, the color matching functions are data from the first step of visual processing. CIE color matching functions are one of many transformations of receptor sensitivities combined with pre-retinal absorptions. They provide a very useful tool to predict matches. Under any viewing condition it can calculate whether two halves of a split spot of different spectral composition will match. The physiological sensitivity functions have more crosstalk than the standardized CIE psychophysically derived transformations of them. Both cone-sensitivity functions and color matching functions have considerably more crosstalk than photography.

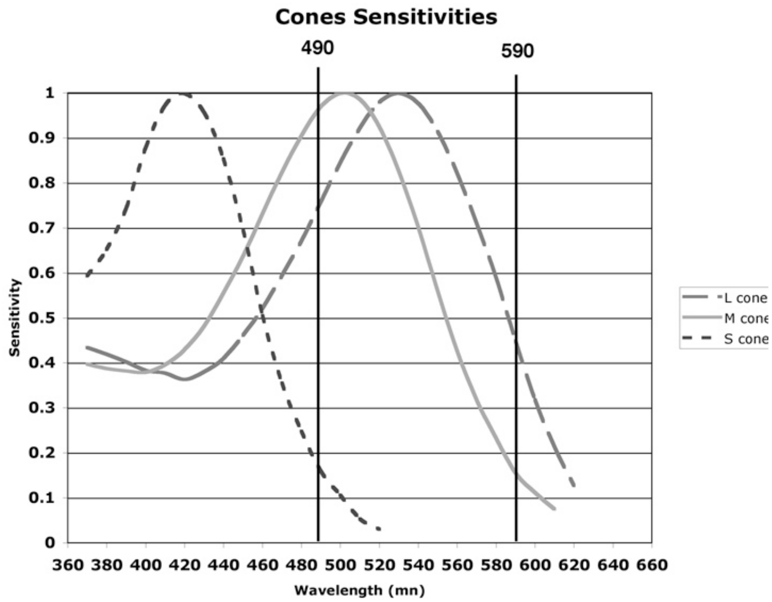

Figure 7 is the plot of cone sensitivity functions from Dartnall, Bowmaker and Mollon data. The black vertical lines are at 490 and 590 nm.

3.0 CROSSTALK

Color channel crosstalk[22] is the biggest difference between the narrow, non-overlapping sensitivity functions of practical imaging and the broad, overlapping sensitivities of human vision. Let us consider three papers; white, gray and red; illuminated by three narrow-band LEDs; 625, 530 and 455nm. The Total Long-wave Response (TLR)

$$TLR = \left(\left[I_{625} \bullet R_{625} \bullet LS_{625}\right] + \left[I_{530} \bullet R_{530} \bullet LS_{530}\right] + \left[I_{455} \bullet R_{455} \bullet LS_{455}\right]\right)$$

where I is the incident illumination, R is the % reflectance and LS is the long-wave channel's sensitivity for each wavelength used. The long-wave sensors' response to 625nm light is a primary response. The long-wave responses to 530 and to 455nm are both crosstalk.

Imaging systems minimize crosstalk as much as possible. With no crosstalk $LS_{530} = 0$ and $LS_{455} = 0$, then TLR = (I_{625} xR_{625} xLS_{625}), limited to the primary response. The white paper has R_{625x}=90%, R_{530}=90%, R_{455}=90%; the red paper has R_{625}=90%, R_{530}=12%, R_{455}=8%. With no crosstalk, TLR of both white and red papers is (0.9 x I_{625} xLS_{625}).

The broad human sensitivities generate substantial crosstalk. The red paper shows a significant change in responses with illumination. With crosstalk the TLR is the combination of 90%, 12% and 8% reflectances in the proportions determined by the values of I and LS. Substantial increases in 530 and 455 illuminants relative to 625 reduce the fraction of primary response in the TLR. The dilution of 90%-long-wave information with 12% and 8% moves the 90% value toward 50%. Crosstalk reduces high-chroma colors to colors with a substantial amount of gray. One signature of crosstalk is that it reduces the chroma of the red paper and all other highly colored papers. The amount of reduction depends on the proportions of the illuminants. Parallel analyses hold for all color channels.

3.1 Crosstalk – a Signature of the Color Constancy Mechanism

As discussed above, our understanding of the physiology of vision went through a major shift in the second-half of the twentieth century. Earlier thinking focused on pools of receptors to explain threshold sensitivity measurements, i.e. Ricco's and Pipers' Laws. However, the work of Kuffler, Barlow, Hubel, Wiesel, DeValois, Daw, Campbell, and Zeki transformed thinking about vision into the need to understand spatial comparisons. That is what the post-receptor physiology does---it makes spatial comparisons.

Analysis of color channel crosstalk supports color theories based on spatial comparisons. These theories suggest that human vision builds independent L, M and S lightness images by taking ratios of different image areas. The long-wave output calculation uses the ratio of the red paper to the white paper. This ratio changes with relative changes in 625, 530 and 450nm illumination because the proportions of crosstalk contributions change. This argument holds for colored papers, but not for achromatic ones. By definition a white and gray papers have the same reflectance for all wavelengths. When the crosstalk component is the same as the principle component the ratio of gray to white is constant for all changes in illumination. Consider the ratio of the TLR for the neutral gray paper (Reflectance Rn) to the TLR of the white paper (Reflectance Rw). By definition both the white and gray have the same reflectance for all three illuminants.

$$Ratio = \frac{\left(\left[I_{625} \bullet Rn_{625} \bullet LS_{625}\right] + \left[I_{530} \bullet Rn_{530} \bullet LS_{530}\right] + \left[I_{455} \bullet Rn_{455} \bullet LS_{455}\right]\right)}{\left(\left[I_{625} \bullet Rw_{625} \bullet LS_{625}\right] + \left[I_{530} \bullet Rw_{530} \bullet LS_{530}\right] + \left[I_{455} \bullet Rw_{455} \bullet LS_{455}\right]\right)}$$

$$when$$

$$Rn_{625} = Rn_{530} = Rn_{455} = c_1$$

$$Rw_{625} = Rw_{530} = Rw_{455} = c_2$$

$$Ratio = \frac{\left(\left[I_{625} \bullet c_1 \bullet LS_{625}\right] + \left[I_{530} \bullet c_1 \bullet LS_{530}\right] + \left[I_{455} \bullet c_1 \bullet LS_{455}\right]\right)}{\left(\left[I_{625} \bullet c_2 \bullet LS_{625}\right] + \left[I_{530} \bullet c_2 \bullet LS_{530}\right] + \left[I_{455} \bullet c_2 \bullet LS_{455}\right]\right)}$$

$$Ratio = \frac{c_1 \left(\left[I_{625} \bullet LS_{625}\right] + \left[I_{530} \bullet LS_{530}\right] + \left[I_{455} \bullet LS_{455}\right]\right)}{c_2 \left(\left[I_{625} \bullet LS_{625}\right] + \left[I_{530} \bullet LS_{530}\right] + \left[I_{455} \bullet LS_{455}\right]\right)}$$

$$Ratio = \frac{c_1}{c_2}$$

The ratio of neutral gray papers to white is completely unaffected by the spectral composition of the illuminants. This is not true for colored papers. The ratio of red to white depends on the crosstalk contributions controlled by the overlap of sensitivity functions and proportions of spectral illuminants. The independence of grays and the dependence of colored papers on spectral illumination is an important signature of crosstalk.

4. DEPARTURES FROM PERFECT COLOR CONSTANCY

Color Constancy experiments show that the appearance of objects is almost constant with spectral changes in illumination. Incomplete adaptation and Spatial Comparisons work by very different mechanisms. One uses a mechanism responsive to changes in illumination. The other is responsive to the crosstalk found in making spatial comparisons. By carefully studying the individual color matches we can learn about the underlying mechanisms of color constancy.

4.1 Incomplete Adaptation Predictions

As the explanation of constancy, von Kries suggested that changes in spectral illumination caused relative changes in receptor sensitivities (called adaptation).[23] Incomplete-adaptation hypotheses assume that the departures from perfect constancy are the result of imperfect adjustments to changes in illumination. Since the incomplete adaptation hypothesis is controlled only by illumination changes, it predicts that gray and red papers will have identical constancy departures. In other words, the lack of complete adaptation should cause color shifts in the same direction in color space and they should have the same magnitude.

4.2 Spatial Comparisons Predictions

Let us analyze color constancy assuming that vision is controlled by a number of independent channels using spatial comparisons. Retinex uses spatial comparisons within a color channel to establish relationships across the entire image, and then it compares the three color channels to generate appearance. Here relative quanta catch within a channel is more important than quanta catch at a pixel.

Recent studies[24] of the departures from perfect constancy highlight the role of crosstalk. In Retinex, the long-wave output calculation uses the ratio of the all papers to the white paper (the maxima in each channel). For colored papers this ratio changes with relative changes in 625, 530 and 455 nm illuminations, but not for achromatic ones. These recent experiments used 27 different combination of 625, 530 and 445 light. Matching data (Figure 8) show that gray papers showed little change in matching with 27 illuminants, while colored papers show significant changes in appearance consistent with sensor crosstalk. Discrepancies from perfect constancy are consistent with three-channel crosstalk in spatial comparisons. They are inconsistent with incomplete adaptation which predicts that gray paper change as much as colored ones.[14]

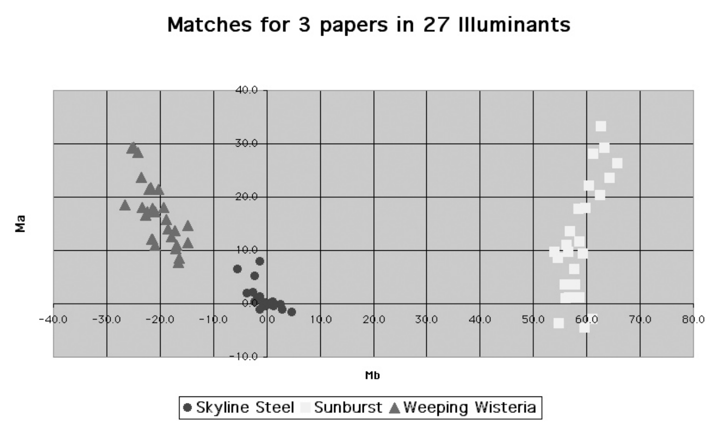

Figure 8 plots in Ma Mb space the average match for all 27 illuminants for three different papers. Sunburst is a low chroma yellow; and Weeping Willow is purple paper; Skyline Steel is a neutral gray. MLAB space[25] is derived directly from Munsell Hue: it mimics the familiar shape of L*a*b* space, but avoids its isotropic distortions. The matches for the yellow paper (Sunburst) are spread over 37.7 units on the Ma axis and over 11.7 units on the Mb axis. The matches for the purple paper (Weeping Willow) are spread over 21.8 units on the Ma axis and over 11.8 units on the Mb axis. The matches for the gray paper are clustered around 0.0. The mean Ma value is 0.8 ± 2.2; the mean Mb value is -0.3 ± 2.0. For gray there is nearly no change in match with illumination.

5. DISCUSSION

Despite the seductiveness of Ives's "natural color" idea, all reproduction processes avoid crosstalk because it severely limits color gamut; spectral crosstalk compresses the range of chromatic colors. At the receptor stage, the achromatic scale from white-black has to be significantly greater range than the range of red-cyan. However, human vision compensates for enormous spectral overlap (Figure 5) by post-receptor processing. We see this in the Munsell Book of Color. The Munsell Book is the result of asking observers to select papers that are equally distant in color appearance. The observers equated chroma and lightness and hue. In this visually isotropic Munsell Color Space, the distance between maximum red (5R5/14) and maximum cyan (5BG 5/10) is equivalent to 12 lightness steps. However, white to black has only 8 equivalent-sized steps. In appearance, the range of chromatic colors is greater than that of achromatic colors. Vision over-compensates for crosstalk and stretches the chroma of cone responses. Until the advent of electronic imaging such opponent processing has been difficult in photography. The exception is in the graphic arts where plate making has used color masking to increase the chroma of colors.

The second post-receptor process involving crosstalk is color constancy. Color appearance is nearly independent of the spectral content of the illumination, and hence the quanta catch of the cones. This second post-receptor process has to generate a set of visual responses independent of the overall intensity and spectral composition of the illumination.

Ratios of adjacent cone responses made by spatial comparisons provide a mechanism for illumination independence. The ratio of responses of two adjacent cones having the same spectral sensitivity is independent of overall changes in illumination because the numerator changes by the same factor as the denominator. If the cone sensitivity curves had no crosstalk, then color constancy would be perfect. As we have seen here, there is considerable crosstalk and the departures from perfect constancy correlate with that crosstalk. Colored papers show color shifts and gray papers do not.

6. CONCLUSIONS

In summary, Image Makers have opted for narrow, non-overlapping spectral sensitivities, so as to minimize crosstalk. Humans, limited by the chemistry of visual pigments, use broad, overlapping sensitivities, with additional neural mechanisms that overcompensate for crosstalk. These post-receptor mechanisms stretch the chroma of cone signals.

Crosstalk can be use to differentiate between different mechanisms for color constancy. Color matches with changing illumination are consistent with a spatial comparison mechanism and inconsistent with incomplete adaptation.

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