This is a preprint of

6807-2 paper in SPIE/IS&T Electronic Imaging Meeting, San Jose, January, 2008

COLOR GAMUTS IN DIM ILLUMINATION

John J. McCann
McCann Imaging, Belmont, MA 02478 USA

COLOR GAMUTS IN DIM ILLUMINATION

John J. McCann*
McCann Imaging, 161 Claflin St. Belmont, MA 02478, USA

ABSTRACT

Rods act as color receptors in dim illumination. Several recent studies have measured the range of colors at low-light levels in different illuminants. This paper reviews these results and adds new experiments using long-wave-rich illumination, appropriate for rod and long-wave cone interactions. The experiment illuminates Munsell ColorChecker papers with 546, and then with 455 nm narrowband lights at radiances below cone thresholds. The third illuminant is 625 nm light, above cone threshold. Observers make asymmetric matches of the ColorChecker using a digital computer display. The observers make these matches while viewing the entire ColorChecker. Observers report a wide range of colors from the combination of cone response to 625 nm plus rod response to 546 nm light. The same is true with the combination of cone response to 625 nm plus rod response to 455 nm light. Although the color matches vary with the ColorChecker's reflectances, the range of colors is the same. Since these experiments use illuminants more appropriate for rod-cone interactions, they measure a much greater color gamut than photopic illuminants. They also provide new data that clarifies how the rod information interacts with the cone-cone color channels. Color appearances indicate rods share M- and S-color channels.

Keywords: rod and Lcone color interactions, dim illumination, firelight, spectral illumination

1. INTRODUCTION

Since the late 1960's, many authors have reported colors from rod and L-cones (See reviews in Stabell and Stabell[1] (1998), Buck[2] (2004), and McCann, Benton, and McKee[3] (2004). Recent papers have studied the range of colors at low-light levels in different illuminants. This paper reviews these results, and adds new experiments using long-wave-rich illumination, appropriate for rod and long-wave cone interactions. The experimental results agree with and extend previous results. Our experiments use illuminates appropriate for rod-cone interactions, namely with 100 times more long-wave than short-wave light. Under these conditions, we measure a wide range of colors. Also, these experiments provide new data that clarifies how the rod information interacts with the cone-cone color channels.

Shin et al.[4] in 2004 reported the color observed in Photopic, Mesopic, and Scotopic conditions. They used D65 fluorescent lamps illuminating 48 squares subtending 10°. They matched these color appearances with a color CRT screen. They matched each paper individually in a middle-gray N/5 viewing booth environment. The color matches at 1000 lux included many colorful objects. The matches at 0.01 lux cluster near gray.

Pokorny et al.[5] in 2006 used color-naming experiments to describe colors in dim light. They studied 24 OSA-UCS chips in 5000°K fluorescent illumination. Their experiments covered the illumination range of 10 to 0.0003 lux. They viewed the 24 square samples (8° to 10°) on a black matte table. They reported a general loss of colorfulness, yet reported seeing color generated by rod and L-cone interactions.

In much earlier work, in 1969, McCann and Benton used narrow-band illumination on a Mondrian display of ColorAid papers.[6] After total dark adaptation they asked observers to increase the amount of 546 nm light until they saw a variety forms and shapes. Observers reported a range of lighter and darker achromatic areas with this wavelength, one log unit above absolute rod threshold (measured by dark adaptation threshold vs. time). Then observers adjusted 656-nm light alone until they saw forms. At 0.7 log unit above L-cone threshold they saw light and dark areas in a uniform red wash. No variegated color was seen. When these 546- and 656-nm lights were combined, observers reported a wide range of colors. The 546-nm light was nearly 2 log units below M-cone threshold, showing that these colors were from rod and L-cone interactions. Additionally, observers showed they needed considerably more 656-nm light than 546-nm light for these color interactions.

McCann and Benton[6] also used dual-image monochromators to illuminate black and white film separation transparencies of a complex image. They changed the monochromator wavelength from 400 to 600nm illuminating a black and white (Wratten 58) green record of the scene. At high luminance levels the image had no variegated color, but the hue of the color wash changed from violet, blue, green, yellow, to red with changing wavelengths of illumination. Repeating the experiment after dark adaptation, just above absolute threshold, the color wash was gone for all wavelengths below 600 nm. Observers reported that that the achromatic images were brightest at 500 nm and decreased with longer and shorter wavelengths. When experimenters added a black and white (Wratten 24) red record in 656-nm light to the middle-wave record, observers reported a variety of different colors. Observers were asked to change the wavelength illuminating the W58 record while adjusting the radiance for best color. They reported the colors in the scene were constant. McCann and Benton asked observers to match the colors seen in rod-Lcone interactions (in the left eye) to cone-cone colors of the same scene at high radiance in a second image monochromator (right eye). They reported that rod-Lcone colors are best matched with 656 nm and 495 nm light. These results suggested that the rod information was shared with both M- and S-color channels.[6]

The recent Shin et al. and Pokorny et al. studies measure the range of colors found using normal photopic illuminants. They have roughly uniform radiance across the human visual spectrum. This spectral distribution is well suited for equal stimulation of the long-wave (L), middle-wave (M), and the short-wave (S) cones. Figure 1 plots the relative rod and cone thresholds (amount of light at threshold vs. wavelength). The vertical axis plots the relative amount of light needed to obtain a threshold response vs. wavelength. The rod sensitivity function is the photopic luminosity curve, with the relative sensitivity to light normalized to 1.0 at 507 nm the peak of rod response. The cone sensitivities are from Stockman's and Sharps' studies of cone color matching functions. [7]

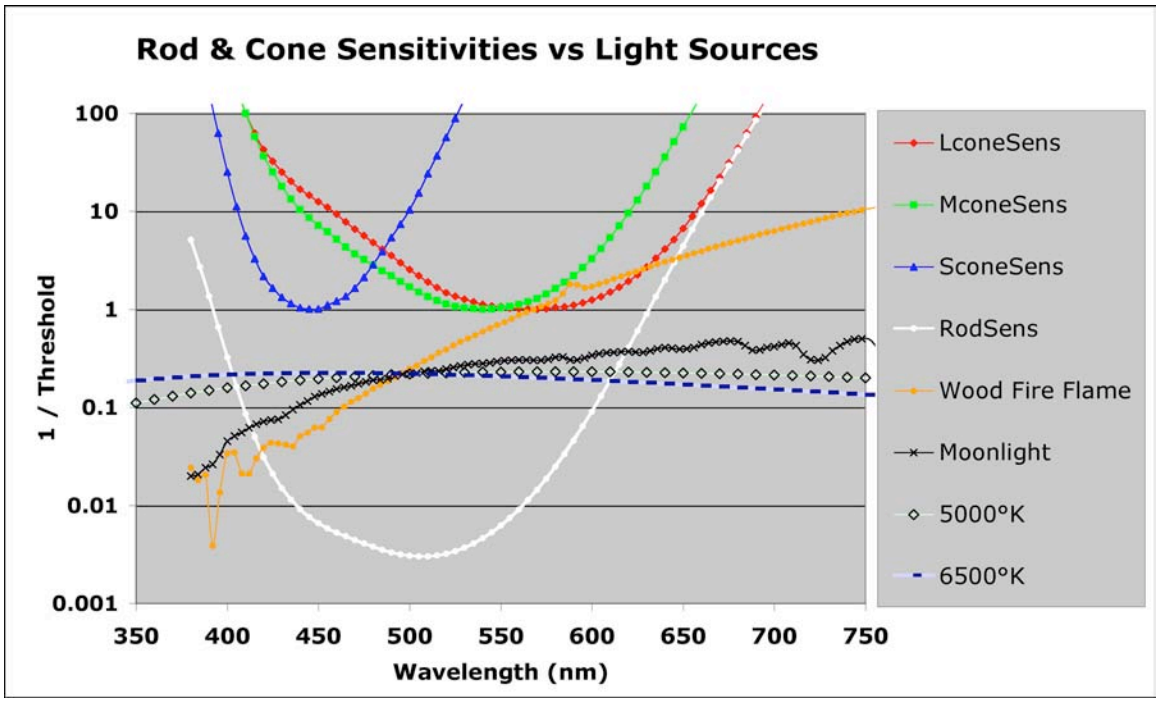

Figure 1 plots of the amount of light necessary for a threshold response to light as a function of wavelength for rods and L-, M-, S-cones. The data is the scotopic sensitivity function and cone fundamentals from Stockman and Sharpe [10]. The figure also superimposes the emission spectra of illuminants on the threshold sensitivity curves for the L-, M-, and S-cones and the rods. Firelight, moonlight, 6500° K and 5000°K spectra are normalized at 500 nm. At these intensities the 6500° K and 5000°K spectra are above threshold for rod only. Increasing the intensity of the 6500° K and 5000°K spectra will stimulate rods alone until the illuminant stimulates all cones and rods. Unlike firelight, that is above both rod and L-cone thresholds, the 6500° K and 5000°K spectra go form rods only to all cones over a very narrow range of intensities.

Recently measurements documented that firelight has the appropriate ratio of long to short-wave light for see colors with rods and long-wave cones. McCann measured the exitance of wood-fire to be equivalent to 1700°K and candlelight to be 2000°K. [8]. Firelight spectral emissions are well suited to generating supra-threshold response for both rod and L-cones. Such illuminants, rich in long-wave light, are optimal for rod and Lcone interactions. Since the rods are between 100 to 1000 times more sensitive than the Lcones, illuminants need to have at least 100 times more long-wave radiance. Light from burning wood, candles, and 1000°- 2000° K black body radiators have an appropriate spectral emission for observing the maximum range of colors in very dim illumination.

Figure 1 includes the spectral exitance of firelight (~1700°K), moonlight, along with 5000°K, and 65K blackbody curves superimposed on L-, M-, S-cone and rod sensitivity curves. (Shin et al. and Pokorny et al. used fluorescent lights with nominal specifications of color temperature. The actual spectra will be different from the nominal spectra.) These spectra are all normalized to the same value at 500nm. Moonlight, 5000°K, and 6500°K lights severely limit the opportunity for rod/L-cone interactions. When L-cones are at form threshold, the M- and S cones are at, or above cone threshold. When rods are at form threshold the L-cones are 100 to 1000 times below cone threshold. Moonlight[8] has a higher long-wave content than 5000°K and 6500°K light, but only firelight has sufficient long-wave light to selectively stimulate rods and long-wave cones.

The combination of these recent and older experiments still leave a number of important questions unanswered. There are conflicting claims and interpretations. Shin's D65 matches support the traditional additive mixture of colorful cone and achromatic rod images. Pokorny's 5000° K color naming experiments report color names even in rod only conditions. McCann and colleagues report much more colorful images using illuminants with 100 to 1000 times more 656nm light than 500nm light. Rod / Lcone color interactions require long-wave rich illuminants. The experiments in this study add color matches in dim light using narrow band illumination. These experiments measure the range of colors seen by rod and L-cone interactions under more optimal conditions than 65K and 5000°K. This data will allow us to discuss the many different conclusions about how rod signals interact with the cone-cone color channels.

2. ASYMETRIC COLOR MATCHES

A previous article[9] measured the range of colors observed in candlelight and narrowband illuminants. Both long-wave-rich illuminants showed a greater range of colors than reported for 5000°K and D65 light. This article describes the range of colors observed with three narrow-band lights. We used 625, 546 and 455 narrow band illuminants at dim light levels. The 625nm light illuminated the color checker so that the Lcones were above threshold. Both the 546 and 455 nm lights illuminated the ColorChecker so that it was above rod threshold and below M- and S- cone thresholds. The observers made asymmetric color matches by adjusting the digits controlling a computer LCD display.

The experiment asked observers to match all the ColorChecker squares in 625 plus 546nm light. Then, it asked them to match the squares in 625 plus 455nm light. Each of the colored papers had a different reflectance in 546 and 455 nm light. That would suggest that the matches should be different for each colored paper. The experiment compares the range of colors observed in each pair of illuminants.

2.1 Methods

We used asymmetric color matching, using one eye at a time. The left eye adapted independently to the above cone threshold LCD display and the right eye to the dim reflectance target. We used a Macbeth ColorChecker reflectance card with 18 color and 6 gray squares. The squares were viewed in narrow-band illumination. Matches were made on LCD display of a PowerBook PV G4 15" using AC power. Observers were asked to use Photoshop controls to adjust the hue, saturation, and lightness of each area independently. The observers began by adjusting the gray background to appear as close as possible to the gray surround in the reflection target. Then, they adjusted each of the 24 squares, one at a time, until the entire scene was the best possible representation of the ColorChecker target. Observers were asked to keep adjusting the colors until each area had the best possible color relationship to all other colors in the display. The above cone-threshold display is sharper, brighter and has less visual noise than the dim images. In each experimental session the observer started with a 3-color image of the ColorChecker on the screen (Start Image, Fig 2). Observers spent about one-half hour making a first pass at matching the background and the 24 squares. The entire session took at least one hour. This lengthy procedure insured that the two eyes had time to reach an asymptote in adaptation to the LCD screen in the left eye, and the dimly lit ColorChecker in the right eye. There were two observers that each made multiple matches, two or more, of the entire display. The results in each case, and for each observer were very similar.

Concerns about uniformity of the LCD display uniformity made us choose to present individual results rather than averaged data. Each square subtended about 4.6°.

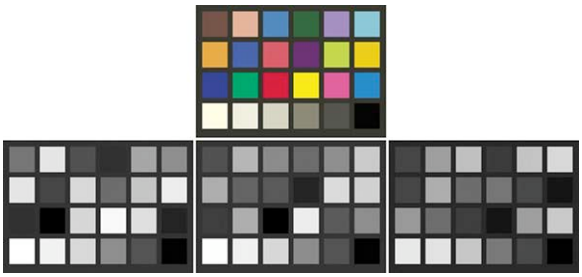

Figure 2. (top) shows the digital color image used in the *Start Image* of each matching session; (bottom) show the digital R (left), G (middle), B (right) separation images used in making the color image on the display.

Figure 2 shows the digital image of the Start Image display. It had a maximum luminance of 4.6 cd/m^2, x=0.30, y=0.33

2.2 ColorChecker Illumination

A single 625nm LED illuminated a 3.5 x 8 inch diffuser. The diffused illuminated the ceiling of a dark room that indirectly illuminated the papers in a Munsell ColorChecker test target. A second 455 nm LED with an independent power supply illuminated the same diffuser. The third illuminant was a tungsten lamp with a Wratten 93 filter (546 nm dominant wavelength) with neutral density filters. We adjusted each illuminant's intensity independently.

In order to measure the largest gamut of rod and L-cone colors we need short-wave stimuli just below M-cone or S-cone threshold. We also need the long-wave stimuli adjusted for the best colors. With the 546 nm light we established that the ColorChecker was below M-cone threshold by the lack of colors in the ColorChecker, the noisiness of the image and the lack of edge sharpness. The 625nm light was adjusted for best range of colors in combination with the 546nm light. The 455nm light was adjusted for the best range of color in combination with the 625 nm light. At this intensity of 455 nm light, the ColorChecker appeared a noisy neutral gray, and was unsharp.

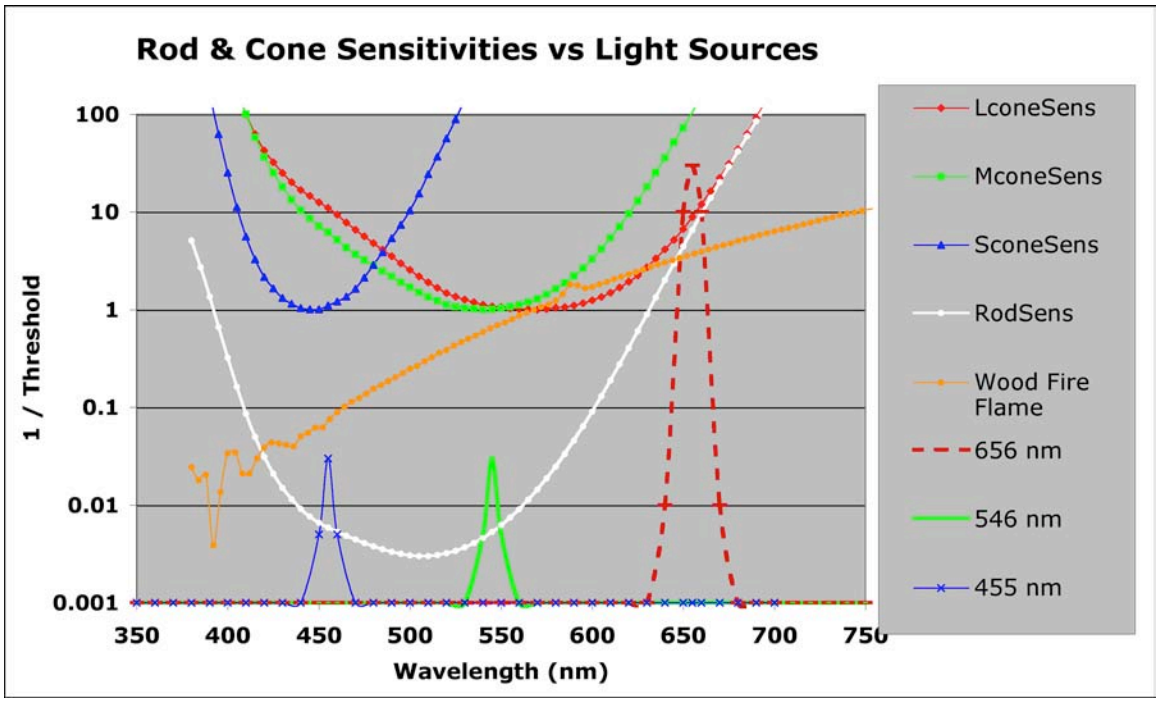

Figure 3 superimposes the emission spectra of firelight and the 625, 546 and 455nm narrowband illuminants adjusted to form thresholds.

3. COLORS FROM NARROW-BAND ILLUMINATION

We measured the range of colors observed at low light levels using illuminants appropriate for rod and L-cone interactions. One illuminant was a narrowband 546 nm light, adjusted to be above rod threshold, and below M-, or S-cone thresholds. The other illuminant, 625 nm light, was set to be above L-cone threshold. Under these conditions, there is about 100 times higher 625 nm radiance, than 546nm radiance. The test target was the MacBeth ColorChecker made up of 24 papers. Observers matched the appearance of the 24 papers by adjusting a computer monitor at radiances above cone threshold. The task involved viewing all colored papers at once, and then viewing all matches at once. Observers' matches show a distribution in display color space consistent with rod and L-cone color interactions.

In a second set of matches, we replaced the 546nm illumination with 455nm light. Again, observers matched all 24 papers, viewed simultaneously. Each of the colored papers was matched by a different triplet of R,G,B display digits because of the change in reflectivity in 455nm light.

3.1 Rods with 546nm light alone

In a control experiment we used only 546nm narrowband light below cone thresholds. In this condition, the ColorChecker papers appeared achromatic. Observers adjusted the hue, saturation and lightness of each square sequentially until each of the squares in the computer display appeared to match the corresponding papers. Observers selected digits close to neutral gray. Figure 4 shows the RGB separations of one observer's matching image. Observe that the three separations of the starting image have different lightnesses for colored papers and the same lightnesses for gray papers (Figure 2). In Figure 4, the R, G, B separations are nearly identical. This shows that the observer individually adjusted each colored paper from different R, G, B values to almost the same values.

Figure 4 (top) shows the digital R, G, B separation images selected by observer matching session for narrowband 546-nm light alone. The three separations are nearly identical.

3.2 Rods with 546nm light plus cones with 625 nm light

This experiment used 546 nm light with 625nm light. The matching RGB separation digits are printed in Figure 5. The digits show that the observer chose different separations values for this match. The G and B separations are quite close to each other. The R separation was different.

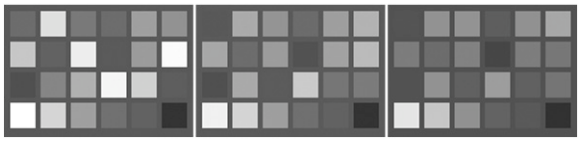

Figure 5 shows the digital R, G, B separation images from matches in 625 plus 546 nm light. For the colored papers, the observer selected nearly the same digits for this G and B separations. The R separation was different digits.

3.3 Rods with 455nm light plus cones with 625 nm light

This experiment used 455 nm light with 625nm light. The matching separation RGB digits are printed in Figure 6. The digits show that the observer chose different separations values for the match. The G and B separations are quite close to each other. The R separation is different.

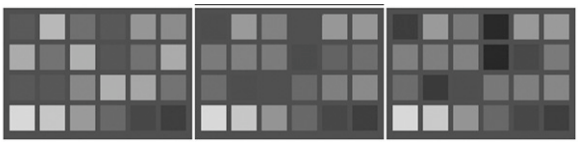

Figure 6 shows the digital R, G, B separation images from matches in 625 plus 455 nm light. For the colored papers, the observer selected nearly the same digits for the G and B separations. The R separation was different digits. The 455 nm G&B separations in this figure are different from those in Figure 5 (G&B separations in 546 nm).

4. DISCUSSION

Each of the authors discussed in the introduction used a different cone color space to evaluate color appearances. We can choose to evaluate these results using L*a*b*, ML Ma Mb, LMS cone responses and MacLeod's highly asymmetric cone L/(L+M), S/(L+M) plot. Each of these colorimetric, appearance, or cone space transforms will stretch the data in a different non-linear manner. Each cone based color transform will affect the distance between two different colors. It will not affect two colors that share the same RGB digits. Is it appropriate to use a cone colorimetric space for evaluating rod-cone color?

Before using any of these nonlinear transforms, we can answer a number of important questions by just evaluating the raw digital data. First, we can plot LCD display digits in its own chromaticity space using:

$$\frac{R_{digit}}{R_{digit}+G_{digit}+B_{digit}}, \frac{G_{digit}}{R_{digit}+G_{digit}+B_{digit}} \quad (1)$$

Using display chromaticity, we can compare the color match chromaticities with the range of colors produced by the display. The gray triangle in Figure 7 plots the chromaticities of all color stimuli produced by the display. The triangle plot the gamut points for Red = 255,0,0 (R), Yellow = 255,255,0 (Y), Green = 0,255,0 (G), Cyan = 0,255,255 (C), Blue = 0,0,255 (B) and Magenta = 0,255,255 (M). The diamonds in Figure 8 plot the display chromaticities of the Start Image. The RGB color image fills the middle of the color space and has chromaticities near Y and C, but not near R, G, B, and M gamut limits.

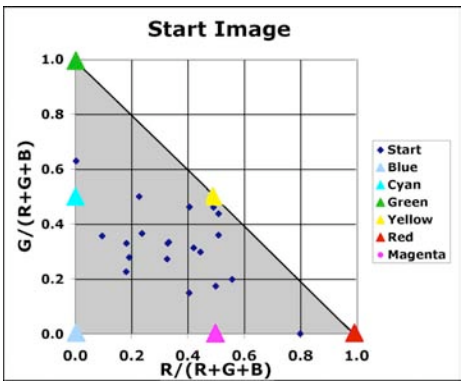

Figure 7 shows the range of display chromaticities possible with the display. The colored triangles show the chromaticities of the vertices of the cubic color space. The diamonds plot the colors in the Starting Image of the ColorChecker.

4.1 Rods with 546nm light alone

Figure 8 plots the LCD chromaticities of the matches made in 546 nm light. In the display chromaticity plot the matches for 546nm alone fall near a single point that characterizes achromatic grays. This data supports Max Schultze's Duplicity Theory and Shin et al.'s report that appearance with rods is achromatic.

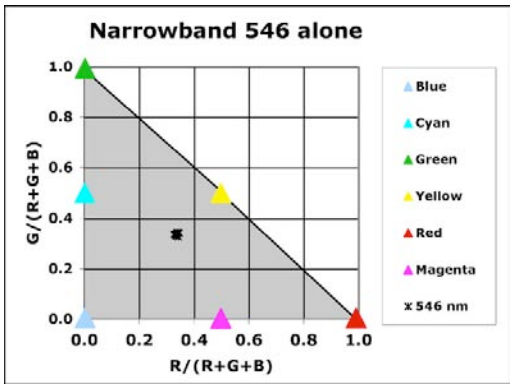

Figure 8 plots the LCD chromaticities of ColorChecker matches in 546-nm light alone.

4.2 Rods with 546 or 455 nm light plus cones with 625 nm light

The separations in Figures 5 and 6 showed that the rod's sensitivity curve interacts with the ColorChecker's colored reflectances to make observers make different matches for the same paper. The chromaticity data in Figures 9 and 10 show that even though the individual matches were different, the range of colors is approximately the same. The observer color matches have separations near the locus of chromaticities when G=B in digital values.

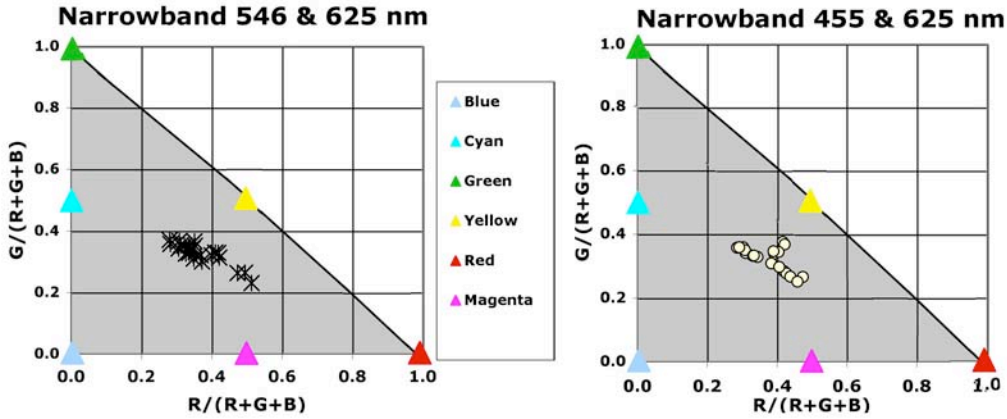

Figure 9 plots the display chromaticities of 625 and 546 nm light (left) and 625 and 455 nm light (right).

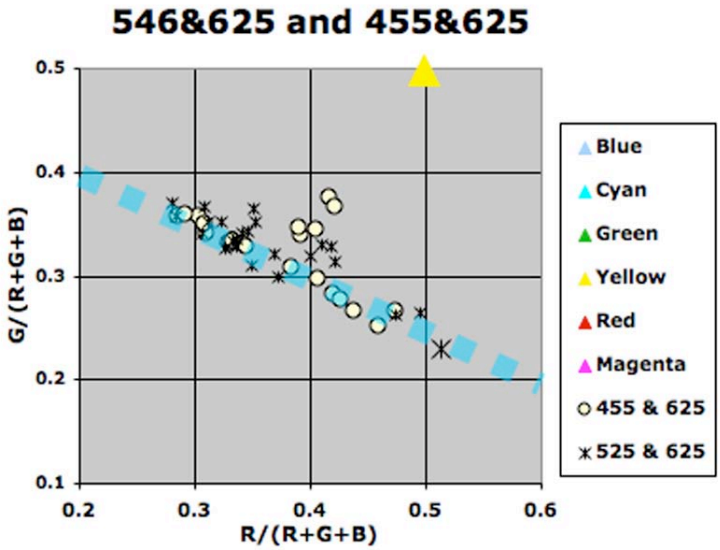

Figure 10 superimposes and enlarges the display chromaticities of 625 with 546 nm light and 625 with 455 nm light. The transparent cyan diamonds plot the G=B locus of points along the R-C line in Figure 12.

These results are central to the understanding of the unresolved issues found in the introduction. Clearly these colors are the result of rod and L-cone interactions. Clearly these color appearance are not uniquely different from those found in cone-cone interactions. Rods, as a fourth spectral sensor do not generate a 4D color space. Both these conclusions are shared by McCann and Benton[3], Shin, et al. [4]and Pokorny, et al[5]. The issue is how large a range of colors can be seen in a single image, and how is the rod response processed in the 3D color channels?

A simple color calibration experiment is helpful. Figure 11 shows different displays of color separation information. On the left is the RGB *Start Image*. Here, the R separation record is sent to the display's red channel; G record to green channel; B record to blue channel. If the rods share only the same color channel as the S-cones, as Wilmer[10] suggested, then we must expect the set of two-color combinations found in Figure 11 (center left) with G channel off, that is, equal to black. If the rods share the same M-color channel, as Cao et al.[11] suggested, then we must expect the set of two-color combinations found in Figure 11 (center right) with B channel off.

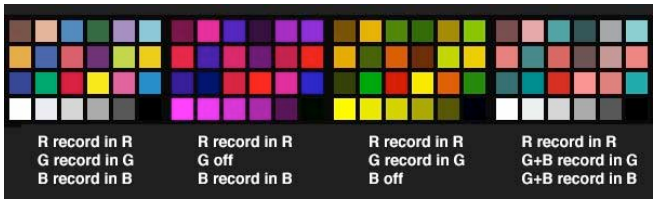

Figure 11 shows the distinctly different sets of colors predicted by R,G,B; R,B; R,G and R,(G+B),(G+B) channels.

However, if the rods share the both M- and S-color channels, as McCann and Benton suggested[3], then we must expect the set of two-color combinations in Figure 11 right. Here, the same information, namely the average of G and B separations, is sent to both the G and B display channels. Using the average of the G and B separation is appropriate because rod peak sensitivity is between M- and S-cone peaks. Each hypothesis has a distinctive set of predicted colors.

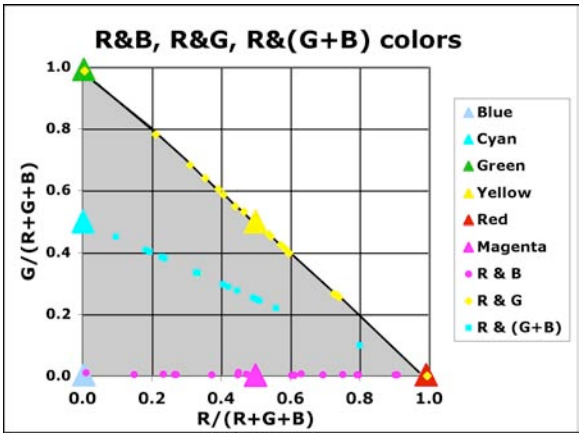

Figure 12 plots the digital values used in Figure 12 as LCD chromaticities.

Figure 12 plots the display LCD chromaticities of each of the three sets of the 24 patches in figure 11. The predictions for the rods sharing the S-color channel are plotted with magenta circles, those for the rods sharing the M-color channel are plotted with yellow diamonds, those for the rods sharing both the M- and S-color channel are plotted with cyan squares.

In a previous paper,[9] we reported that firelight (1 candle at 4 meters) color matches are consistent with the hypothesis that rods share both M- and S- cone channels. Further, the colors have a very much greater range of chromaticities along the R to C line, than the 546 nm - rod only - matches. The results shown in Figures 9 and 10 extend the range of color along this G=B locus. All the matching display chromaticities fall on the R to C line. The results confirm the hypothesis that rod and L-cone color interactions fall on the R to C line. Further, they shows that this wide range of colors requires 100 times more long-wave light than short-wave light. There is insufficient long-wave light with 5000°K and 65K illumination for optimal rod and L-cone color. The above experiments show a substantial range of colors generated by rod and L-cone interactions. This range is smaller than that of 3 color cone responses. All the color matches are consistent with rods sharing both M- and S-color pathways.

So far, we have looked only at the results in the original digital LCD display space. This space has the limitation that it is not perceptually isotropic. We could use L*a*b*, ML Ma Mb, LMS cone responses and MacLeod's asymmetric cone L/(L+M), S/(L+M) color spaces. Only ML, Ma and Mb can claim to be isotropic.[12] The problem is that these spaces transform the original data in different nonlinear manners. Each has advantages and disadvantages. However, none of these transforms will alter the conclusion that rod information is shared by both M- and S- color channels. These transforms can change the shape of the plotted data, but not the underlying result, because they will change overlapping points the same amount. The distance between points will change, but overlapping points will still overlap.

5. CONCLUSIONS

Recent papers using asymmetric color matching and color naming have described a small range of colors from rod and L-cone interactions. These papers used D65 and 5000°K illuminants at low light levels. The experiments in this study measured much greater ranges of color appearances with long-wave rich illuminants appropriate for the relative sensitivities of rods and Lcones. Observers matched a wide range of colors using narrowband 625 with 546nm, and 625 with 455nm illuminants. Plots of matched colors overlapped a wide range of cone-cone colors along the red-cyan axis. These color matches had separation values in which G=B. This suggests that the rod signals are sent to both the S- and M- cone channels.

REFERENCES

[1] U. Stabell and B. Stabell, "Chromatic rod-cone interaction during dark adaptation," J. Opt. Soc. Am. A **15**, 2809-2815, (1998).
[2] S. L. Buck, "Rod-cone interactions in human vision", in *The Visual Neurosciences*, eds. Chalupa, L.M. & J. S. Werner, 863–878, Cambridge, MA: MIT Press, (2004).
[3] J. J. McCann, J. L. Benton, S. P. McKee, "Red/white projections and rod/long-wave cone color: an annotated bibliography", J. Electronic Imaging, **13**, 8-14, (2004).
[4] J. C. Shin, H. Yaguchi and S. Shirori, "Change in Color Appearance in Photopic, Mesopic and Scotopic Vision", Optical Review OSJ, **11**, 266-271, 2004.
[5] J. Pokorny, M. Lutze, D. Cao, & A. J. Zele, "The color of night: Surface color perception under dim illuminations", Visual Neuroscience, **23**, 525-530, (2006).
[6] J. J. McCann and Jeanne L, and Benton, "Interactions of the Long-Wave Cones and the Rods to Produce Color Sensations", J. opt. Soc. Am., **59**, 103-107, (1969).
[7] A. Stockman, & L.T. Sharpe, "Cone spectral sensitivities and color matching", in K. Gegenfurtner & L. T. Sharpe (Eds.), *Color vision: from genes to perception*, 53-87 Cambridge: Cambridge University Press, (1999).
[8] J. J. McCann, "Ideal Illuminants for Rod /L-Cone Color", in Electronic Imaging XI: Processing, Hardcopy, and Applications; R. Eschbach, G. Marcu; Eds., Proc. SPIE, 6058, 1-8, (2006).
[9] J. J. McCann, "Colors in Dim Illumination and Candlelight", Proc. IS&T/SID Color Imaging Conference, Albuquerque, **15**, 313-318, (2007).
[10] E. N. Wilmer, *Retinal Structure and Color Vision*, Cambridge University press, Cambridge, (1946).
[11] D. Cao, J. Pokorny and V. C. Smith, "Matching rod percepts with cone stimuli", Vis. Research, **45,** 2119–2128, (2005).
[12] J. J. McCann, "Color spaces for color mapping", J. Electronic Imaging, **8**, 354-364, (1999).