# Colors in Dim Illumination and Candlelight

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## Abstract

*A variety of papers have studied color 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. Since these experiments use illuminates more appropriate for rod-cone interactions they measure a much greater range of colors. 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.*

## Introduction

A recent paper by Shin et al. reported the color observed in Photopic, Mesopic, and Scotopic conditions [1], extending earlier work. [2] These 2004 experiments used D65 fluorescent lamps illuminating 45 colored and 3 achromatic square papers (JIS equivalent to Munsell) 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. They repeated the experiment in six different illuminances (1000, 100, 10, 1, 0.1, 0.01 lux). The color matches at 1000 lux included many colorful objects. The matches at 0.01 lux cluster near gray, covering only the s small range in L*a*b* units [a*=3 to 6, b*= -7 to 1]. The intermediate illumination show a systematic change from colorful to achromatic consistent with Max Schultze's Duplicity Theory [3] This theory describes two visual mechanisms: a colorful Photopic and an achromatic Scotopic system. Intermediate illuminants are thought of as generating additive mixtures of colorful and colorless images from Scotopic vision.

Pokorny et al. [4] used color-naming experiments to describe color appearances in dim light. They studied 24 OSA Uniform Color Scale 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° visual angle) in a black matte surround on a table. They reported a general loss of colorfulness, yet reported seeing color generated by rod and L-cone interactions.

Over the years many authors have reported colors from rod and L-cones (See Stabell and Stabell [5], Buck, [6] and McCann, Benton, and McKee[7] for reviews). In 1969, McCann and Benton used narrow-band illumination on a Mondrian display of ColorAid papers[8]. After, total dark adaptation they asked observers to increase the amount of 546 nm light until they saw a variety forms and shapes. They reported a range of lighter and darker achromatic areas, 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 .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 also used dual-image monochromators to illuminate black and white film separations 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. They suggested that the rod information was shared with both M- and S-color channels.[8]

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. McCann measured the exitance of wood-fire to be equivalent to 1700°K and candlelight to be 2000°K. [9] These spectral emissions are well suited to generating supra-threshold response for both rod and L-cones. Figure 1 plots the relative rod and cone thresholds (amount of light at threshold vs. wavelength).

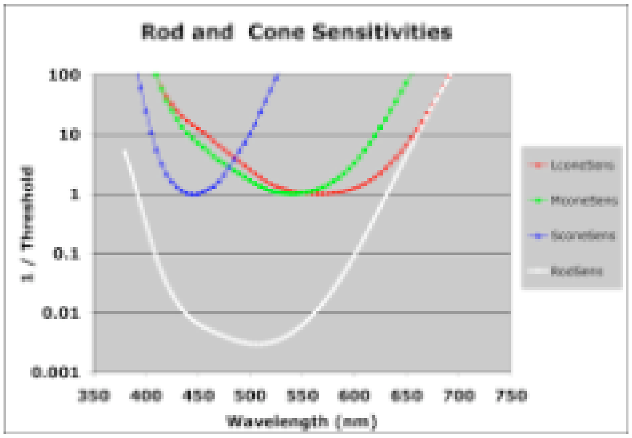

***Figure 1**. Plots of the amount of light necessary for a threshold response to light as a function of wavelength for rods and L-, M-, S-cones. The data is the Photopic sensitivity function and cone fundamentals from Stockman and Sharpe [10].*

Figure 2 adds to Figure 1 the spectral exitance of firelight (~1700°K), 5000°K, and 6500°K lights superimposed on L-, M-, S-cone and rod sensitivity curves. They are all normalized to the same value at 500nm. Both 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 threshold. When rods are at form threshold the L-cones are 100 to 1000 times below threshold. Moonlight [9] has a higher long-wave content than 5000°K and 6500°K light. Only firelight has sufficient long-wave light to selectively stimulate rods and long-wave cone. As well, Figure 2 plots the transmission of 656 nm and 546nm narrowband filters at form threshold [8]. Here by independently determining the thresholds for each wavelength, one can generate optimal rod / L-cone stimuli.

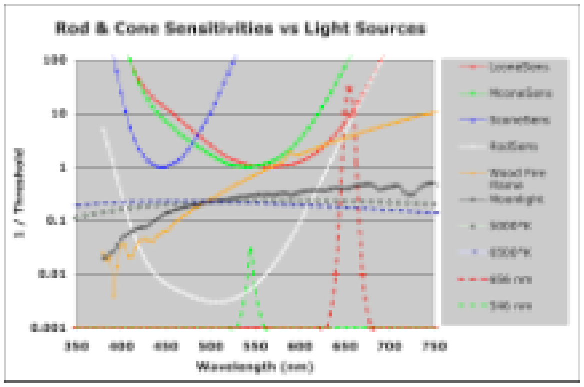

*Figure 2 superimposes the emission spectra of illuminants discussed in this paper on Figure 1. Firelight, moonlight, 6500°K and 5000°K spectra are normalized at 500 nm. Narrow band 546- and 656-nm lights are adjusted to form threshold. [8]*

The experiments in this paper add color matches in dim light using candlelight and narrow band illumination. These experiments measure the range of colors seen by rod and L-cone interactions under more optimal conditions than 6500°K 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.

## *Experiments*

The experiments in this paper used asymmetric color matching [1], 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 24 color squares. The squares were viewed in tungsten, candle, and narrow band illumination. Matches were made on LCD display of a PowerBook PV G4 15" using AC power (set in a fixed position relative to eyepoint and set at the lowest luminance). Observers were asked to use Photoshop Replace Color 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 reflective target. Then, they adjusted each of the 24 squares, one at a time, until the entire scene was the best possible representation of the real target. 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. Asymmetric color matching, above and below cone threshold, is very different from bipartite single spot matching. The above cone-threshold display is sharper, brighter and has less visual noise than the dim images. Observers were asked to keep adjusting the colors until each area had the best possible color relationship to all other colors in the display. In each experimental session the observer started with a 3- color image of the ColorChecker on the screen (Start Image, Fig 3). It's RGB values were from a digital scan of the reflectance target. Observers spent about one-half hour making a first pass at matching the background and the 24 squares. 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. The entire session took about one hour. The squares were viewed at 50 cm and each subtended an angle of about 4.6 degrees.

Figure 3 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.

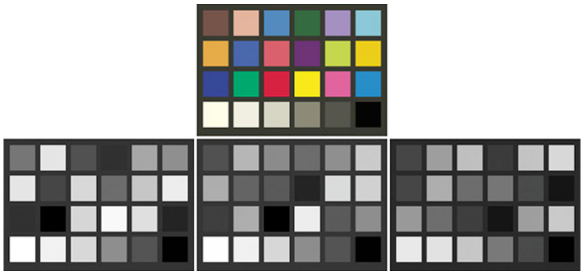

***Figure 3**. (top) shows the digital color image used in the* Start Image *of each matching session; (bottom) show the digital R (left), G (middle), B (right) separation images used in making the color image on the display.*

## Tungsten vs. Candle Illumination

In this control experiment the ColorChecker was illuminated with tungsten bulb in a ceiling fixture behind the observer. The white patch in the ColorChecker measured: [Y=11.5, x = 0.44, y= 0.40]; illuminance is 3.5 lux. This level of illumination produced radiances above all three cone thresholds. The matching image is shown in Figure 4. The matches show a darkening of blues and a color shift of blues toward cyan. The blue separation image shows the most change.

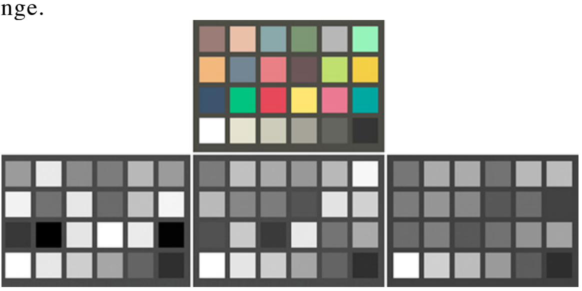

***Figure 4** (top) shows the digital color image selected by observer matching session for tungsten light; (bottom) show the digital R, G, B separation images used in making the color image on the display. The colors chosen here have different color separation images. It is important to note that the colors seen on the printed page do not have the same appearance as those in the viewing booth. These images illustrate the digital values of the matches.*

Next, we repeated experiment using 1 candle placed across the room 4 m from the ColorChecker. The side of the booth prevented candlelight from falling directly on the reflectance target. All light was reflected from the white ceiling, or white walls of the room. The matching image for 1 candle far is shown in Figure 5.

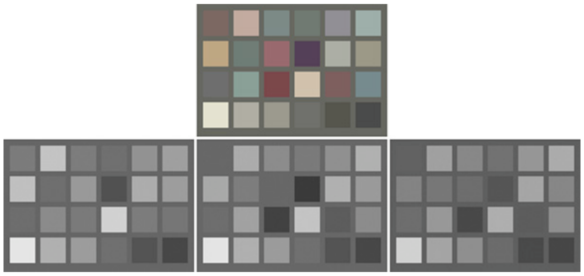

***Figure 5** (top) shows the digital color image selected by observer matching session for 1 candle at 4 meters indirect light. Figure 5 (bottom) show the digital R, G, B separation images used in making the color image on the display.*

The matching image (Figure 5) seen here cannot reproduce the appearance of the color matches because of the white surround on the printed page. Evaluating the images digital values show that the observer lowered the digital values of all of the squares, but held the relationship of the squares to the narrow gray background. Unlike the tungsten match, there were no high chroma blues or greens. Observers matched the ColorChecker hues with mixtures of reds and cyans. The values of the G and B separations have changed from being distinct to being very similar. The original starting image has distinct RGB separations. Long-wave-rich tungsten light changed the blue separation. However, for candlelight illumination at rod and L-cone levels observers makes the G and B separations almost equal. (Fourth square in the second row is somewhat lighter in G.)

## Colors from narrow-band illumination

In order to measure the largest gamut of rod and L-cone colors we need a short-wave illuminant so that observers are just below M-cone threshold and a long-wave illuminant adjusted for the best colors. We used a narrowband Wratten 93 filter (peak transmission 546nm) and neutral density filters on the port of an adjustable voltage tungsten light source. The fact that the ColorChecker was below M-cone threshold was established by the lack of greenish hue, the lack of edge sharpness and dark-adaptation curves measured with the white square in the ColorChecker. The long-wave light was an LED controlled by a variable power supply. The matching procedure was the same as in the previous experiment.

The matching RGB digits are printed in Figure 6. The digits show somewhat greater contrast than those shown in Figure 5. The G and B separations are again quite close to each other.

***Figure 6** (top) shows the digital color image selected by observer matching for narrowband 546 and 625 nm light. Figure 6 (bottom) show the digital R, G, B separation images.*

The final experiment reported here in this abstract is repeating the previous experiment with the 625 nm red LED off. The only illumination was the 546nm narrowband light. Observers again adjusted the hue, saturation and lightness of each square sequentially until all squares had the correct relationship. Figure 7 prints the RGB digits selected for narrowband 546-nm light.

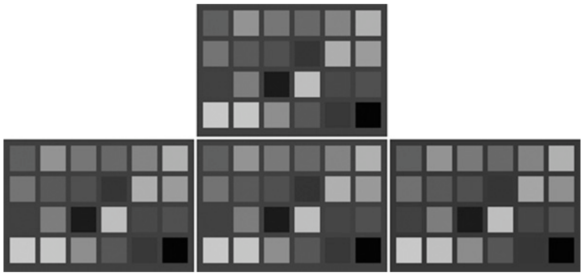

***Figure 7** (top) shows the digital color image selected by observer matching session for narrowband 546-nm light alone. Figure 7 (bottom) show the digital R, G, B separation images.*

Here observers selected digits close to neutral gray. All RGB separations appear very similar.

## Discussion:

Each of the authors, discussed in the introduction, used a different 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. 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:

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

Figure 8 plots the LCD chromaticities of the starting image along with the gamut points for Red (R), Yellow (Y), Green (G), Cyan (C), Blue (B) and Magenta (M). 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.

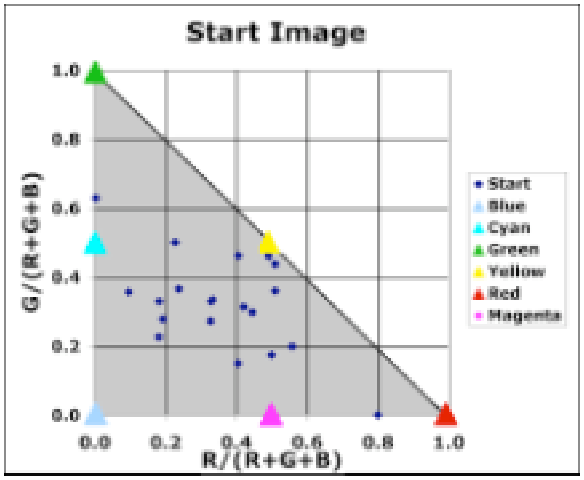

*Figure 8 plots the LCD chromaticities of the Start Image and the R, Y, G, C, B, M gamut limits.*

The control experiment for 546-nm light alone is shown in Figure 9. All data fall in a very narrow range. This data in agreement with Shin's report that all colors converge on gray with limited chromaticity range. Our data shows the mean LCD chromaticities are: [R/(R+G+B) = 0.335 ± 0.004 and G/(R+G+B) = 0.334 ± 0.004]. This may, or may not, be in agreement with Pokorny's color naming experiment because color naming holds for all detectible chromaticities. One cannot discriminate between chromaticity distances by color names. One can only discriminate hue angles, and pink vs. red chroma.

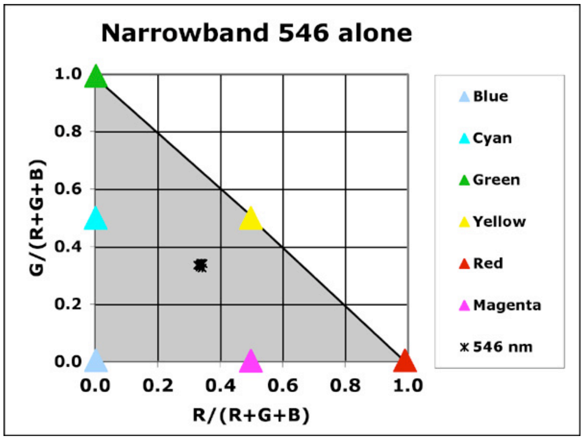

*Figure 9 plots the LCD chromaticities of ColorChecker matches in 546-nm light alone.*

### *Tungsten vs. 1 Candle Illumination*

Figure 10 plots the LCD display chromaticities of the matches in tungsten light above cone thresholds.

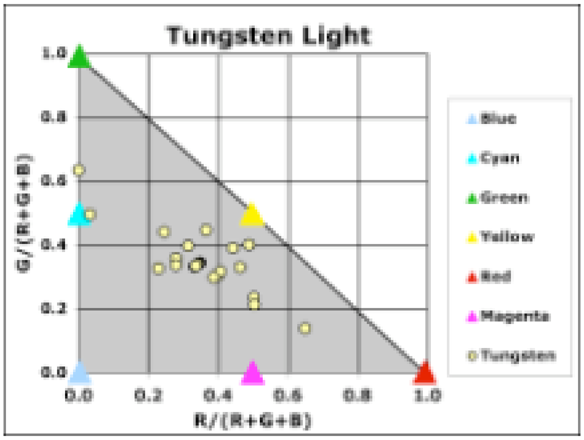

*Figure 10 plots the LCD chromaticities of ColorChecker matches in tungsten light.*

The LCD chromaticity plots show a smaller gamut than found in the starting RGB image. The results show fewer values near blue. Nevertheless the matching chromaticities demonstrate a 3 dimensional color response to tungsten illumination at 3.5 lux.

Figure 11 plots the matching display LCD chromaticities for 1 candle at 4 meters with indirect illumination. All, but one of the squares, have collapsed to be near a line connecting the R and C gamut points. The range of the display chromaticities along that line is smaller than the range found in the Tungsten matches. However, the collapse of the data in the blue yellow direction is dramatic.

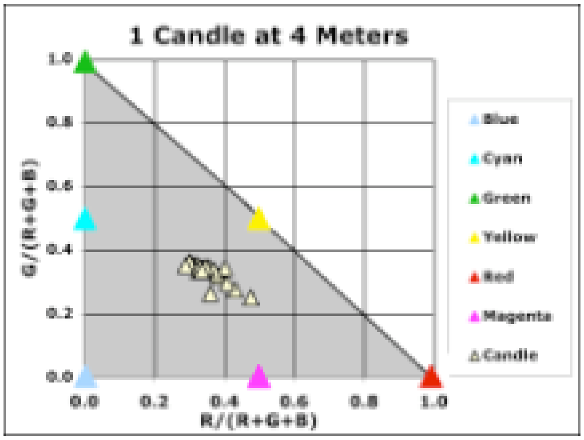

***Figure 11** plots the LCD chromaticities of ColorChecker matches in 1 candle indirect light.*

These results are central to the understanding 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 [8], Shin, et al. [1], and Pokorny, et al [4]. The issue is how large a range of colors can be seen in a single image, and how are the rod response is processed in the 3D color channels?

A simple color calibration experiment is helpful. Figure 12 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 [11] suggested, then, we must expect the set of two-color combinations found in Figure 12 (center left) with G channel off. If the rods share the same M-color channel, as Cao et al [12] suggested, then we must expect the set of two-color combinations found in Figure 12 (center right) with B channel off.

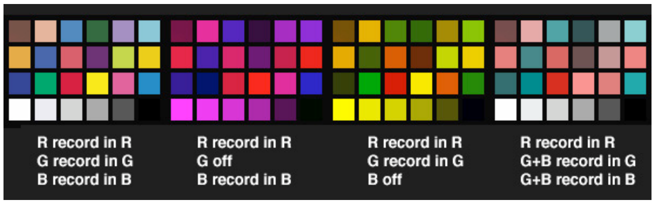

***Figure 12** shows the distinctly different sets of colors predicted by R,G,B; R,B; R,G and R,(G+B),(G+B) channels.*

However, if the rods share the both M- and S-color channels, as McCann et al. suggested [8], then we must expect the set of two-color combinations in Figure 12 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.

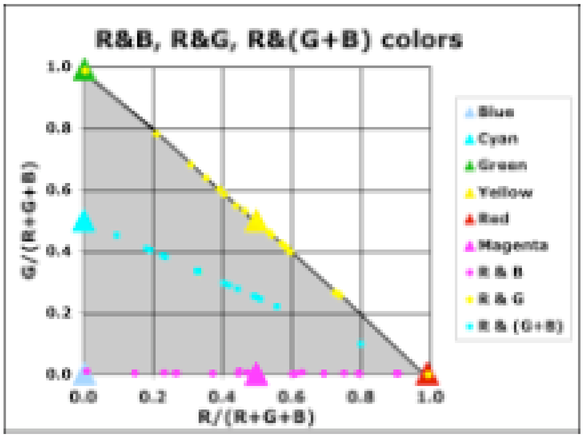

***Figure 13** plots the digital values used in Figure 12 as LCD chromaticities.*

Figure 13 plots the display LCD chromaticities of each of the three sets of the 24 patches in figure 12. 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. When we compare the display chromaticities in 1 candle at 4 meters we find that the 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.

Evaluating the magnitude to this color range must wait until the data is presented in an isometric color space.

### *Narrowband illumination*

So far, we have only discussed the display LDC chromaticities in broadband illuminants. As described above, the maximum color gamut of rod and L-cone interactions is unlikely in any of the illuminated discussed so far. To optimize the color gamut we need to arrange the illumination so as to have maximum rod response, below M-cone threshold. Second, we need to have observers adjust the amount of long-wave light for best color. That data is found in Figure 6 and the LCD display chromaticities are shown in Figure 14.

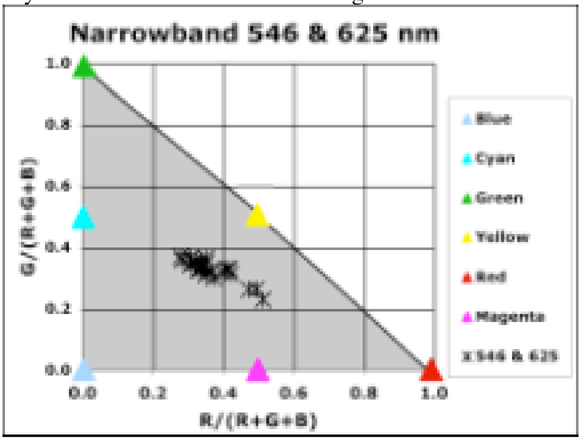

***Figure 14*** *plots the LCD chromaticities of ColorChecker matches in narrowband 546 and 635nm light.*

The matching display chromaticities fall on the R to C line as in the 1 candle experiment. The range of chromaticities is slightly longer (125%) than those in Figure 11. The results confirm the hypothesis that rod and L-cone color interactions. Further, it shows that the range of colors is severely limited by using 5000°K and 6500°K illumination. Moonlight has marginally more long-wave light, and this can explain rainbows in moonlight. However, there is insufficient long-wave light for optimal rod and L-cone color over a wide range of light levels.

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 these colors are consistent with rods sharing both M- and S-color pathways.

So far, we have looked 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 [13]. 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.

## Conclusions

Recent papers using asymmetric color matching and color naming have described colors observed from rod and L-cone interactions. These papers used D65 and 5000°K illuminants at low light levels. The experiments in this paper measured much greater ranges of colors appearances with long-wave rich illuminants appropriate for the relative sensitivities of rods and L-cones. Observers matched a wide range of colors using either dim candlelight, or narrowband 625 and 546nm illuminants. These colors were matched by cone-cone hues along the red-cyan axis. This range of colors shows that the rod signal shares both the M- and S-color channels.

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## Author Biography

*John McCann received a B.A. degree in Biology from Harvard University in 1964. He managed the Vision Research Laboratory at Polaroid from 1961 to 1996. He has studied human color vision, digital image processing, large format instant photography and the reproduction of fine art. He is a Fellow of IS&T (1984). He is a past President of IS&T and the Artists Foundation, Boston. He is currently consulting and continuing his research on color vision. He received the SID Certificate of Commendation, Society for Information Display, 1996. He is the IS&T/OSA 2002 Edwin H. Land Medalist and IS&T 2005 Honorary Member.*