Color Matches in Dim Narrow-band Illumination

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ABSTRACT

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 546 nm radiance. The test target was the MacBeth ColorChecker made up of 24 papers. Observers matched 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 546 nm illumination with 455 nm 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. However, the total range of color matches remained the same as with 546 nm light. The range of colors observed in rod/Lcone interactions is constant, despite changes in spectral content.

Measurements of rod/L cone interactions show a wide range of color appearances when long-wave radiances are 100 times middle- and short-wave radiances. Appropriate illuminants generate a wide variety of colors from rod and L-cone interactions. The observed colors show that rods send their color information to both M- and S-cone channels.

1. INTRODUUCTION

Since the late 1960's, many authors have reported colors from rod and L-cones (See reviews in Stabell and Stabell (1998), Buck (2004), and McCann, Benton, and McKee (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. These experimental results agree with and extend previous results. Since our 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.

Shin et al. (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. (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.

2. OPTIMAL ILLUMINATION FOR ROD/L-CONE COLOR

Recent studies have measured the spectra of firelight and analyzed its effect of color vision at low light levels (McCann, 2006). This work included a history of primate evolution that added a long-wave cone 50 MYA. The results showed that firelight, with about 100 times more long-wave radiance than short-wave radiance was an ideal natural light source for color at lowlight levels. The effects of changing from using all three cones to rod/Lcone color are illustrated in Figure 1. Printed green and blue colors with the same lightness change from appearing different to appearing the same. The integrated reflectance using rods are the same for these two different reflectance papers. In the following experiments we measured the range of colors using light sources that are optimal for rod/Lcone color.

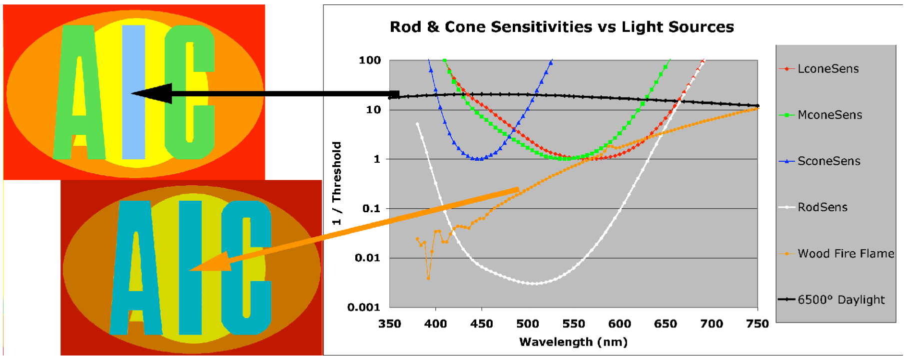

Figure 1. (top left) RGB test target printed with inkjet printer viewed in daylight. Note that the letters A and C appear green, while the letter I appears blue.
(bottom left) Illustration of this print viewed in dim firelight with radiances below M- and S-cone thresholds. Note that all letters AIC appear the same cyan color.
(right) Plots of the amount of light vs. wavelength required for L-, M-, L-cone and rod threshold response to light. As well, the spectra of daylight and firelight.
Firelight has 100 times more long-wave, than short-wave radiance.

3. METHODS AND RESULTS

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 Figure 2 (left). We used a Macbeth ColorChecker reflectance card with 24 color 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 kept adjusting the colors until each area had the best possible color relationship to all other colors in the display. The entire session took at least one hour. This lengthy procedure insured that both eyes had time to reach an asymptote in adaptation to the LCD screen in the left, and the dimly lit ColorChecker in the right eye. Each square subtended 4.6°.

In order to measure the largest gamut of rod and L-cone colors we need a short-wave stimulus below M-cone threshold, and a long-wave stimulus adjusted for the best colors. We used a narrowband Wratten 93 filter (peak transmission 546nm) and neutral density filters with a tungsten light source (Figure 2 right). We established that the ColorChecker was below M-cone threshold by the lack of greenish hue, and the lack of edge sharpness. The long-wave light was an LED controlled by a variable power supply. Observers’ matches covered a wide variety of colors along a red cyan color axis in the above cone threshold color space. We then replaced the 546nm light with 455nm LED light, and used the same matching technique.

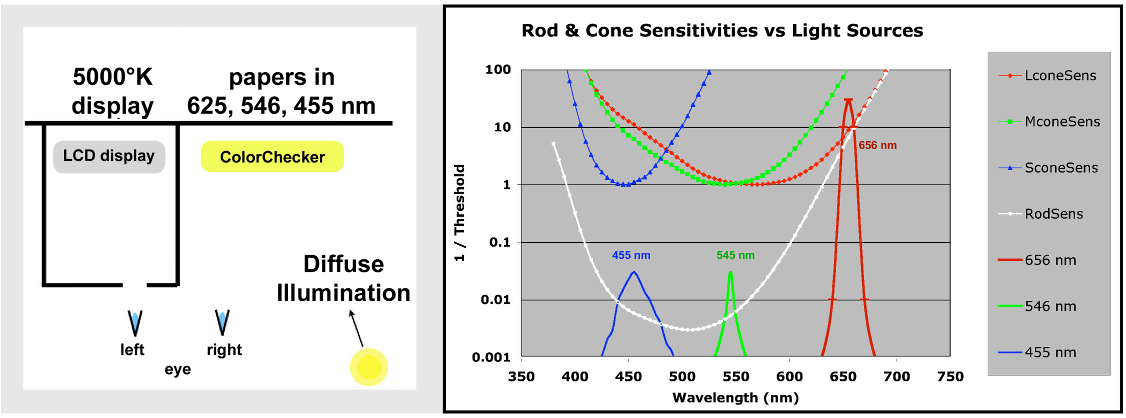

Figure 2. (left) Top view of apparatus. Observers match left eye view of LCD display, above all cone thresholds, to the paper array in dim narrowband light.
(right) Spectra of narrow-band illuminants and receptor sensitivities.

Although the individual color matches depended on the papers' reflectance, the total range of colors observed was nearly constant. In a control experiment we shut off the 625 nm red LED, and used only 546nm narrowband light. Observers selected digits close to neutral gray.

We can 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. We plot the LCD display digits in its own chromaticity space using:

[Rdigit / (Rdigit+Gdigit+Bdigit), Gdigit / (Rdigit+Gdigit+Bdigit)].

When we plot the display chromaticities of the RGB Start Image, it fills the much of the color space and has chromaticity space. When we compare the color matches from 546 & 625nm with those of 455 & 625, the colored papers have different matches. When we compare the R, G and B separation images, we see the pattern that observers selected colors that had the same digital value in both G and B records (McCann, 2008). The separations 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 3 (right) show that even though the individual matches were different, the range of colors is the same. The observer color matches have separations near the locus of chromaticities when G=B in digital values.

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, Shin, et al. and Pokorny, et al. 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? If the rods share only the same color channel as the S-cones, as Wilmer suggested, then we must expect the matches to fall on the Magenta lines in Figure 3. If the rods share the same M-color channel, as Cao et al. suggested, then they will fall on the Yellow lines. However, the data show that rods share the both M- and S-color channels, as McCann and Benton suggested, by falling on the Cyan lines. 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 (McCann, 2008).

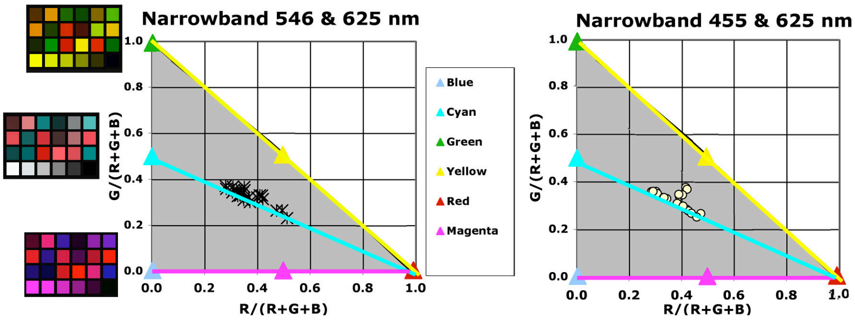

Figure 3. (left) Observer matches in 546 & 625 illumination in display chromaticities. (right) Observer matches in 455 & 625 illumination in display chromaticities. The cyan line plots the locus of chromaticities in which Gdigit =Bdigit on the display.

4. 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 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 and 546nm, and 625 and 455nm illuminants. These colors were matched by a wide range of cone-cone colors along the red-cyan axis.

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