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Red/White Projections and Rod-Lcone Color: An Annotated Bibliography

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ABSTRACT

In the mid 1950's Edwin Land, while developing instant color film, repeated James Clerk Maxwell's 1861 three-color projection experiments. By accident, a two-color red and white projection appeared on the screen. Fascinated by the multicolored images that he saw, Land studied two-color phenomena extensively, published a series of papers and developed a prototype red and white television system with Texas Instruments. This paper describes Land's original Red and White projections using equipment now at the Rowland Institute. In the late 1960's and early 70's McKee, Benton and McCann investigated color images from stimuli that excited only rods and long-wave (L) cones. They used dark adaptation curves, flicker-fusion rates, the Stiles-Crawford Effect, and apparent sharpness to differentiate rod and middle- (M) and short-wave (S) cone responses. They showed that color from rods and L cones under the right stimulus conditions was nearly identical to cone-cone color.

Keywords: Red and white photography, rod-Lcone color, two-color projections

INTRODUCTION

The experiments described in this special edition of JEI are descendents of Edwin Land's experiments in the mid 1950's.[1] Din often told the story about repeating the famous experiment that James Clerk Maxwell presented at the Friday Evening Discourse to Royal Institution on May, 17, 1861. Maxwell demonstrated the first color photograph using three superimposed projections. Each projector had either a red, green or blue filter. Each projector had a black and white photograph taken with the same filter. The photographs were reported to be records of the image information from the long-, middle-, and short- wave visible light.[2] Maxwell's lecture used this superimposed photographic image to support the assertion of Thomas Young's trichromatic theory. However, this event is remembered by photographic historians as the invention of color photography.[3]

Land wanted to see the colors possible in three-color additive projections as a part of his research in developing an instant, three-color subtractive print film. At the end of reviewing a variety of three-color projections, while putting things away, Meroe Morse[4] asked Land why the colors were still there with only red and white light. Land replied, "Oh, that is adaptation". At two in the morning Land reported that he sat up in bed, and said "Adaptation, what adaptation?". The papers in this section result from the fact that Land got up and returned to the lab at 3 o'clock in the morning to see whether these colors could be explained by adaptation. By then, he was well on his way to generating 350 US patents, the majority on the topic of image capture and reproduction. Land recognized instantly that the human visual system was fundamentally different from all image reproduction systems.[5]

RED AND WHITE PHOTOGRAPHY

Land reported his research on red and white photography in a number of papers and lectures from 1955 to 1962. Following that, he started experimenting with real papers and controlled illuminations. This paper begins with an annotated bibliography of the "red and white papers". This body of work is an important prelude to the Mondrian experiments on color constancy.

Color Vision and the Natural Image Part I

[Land, Proceedings of National Academy, 1958][6]

Land's paper began with the statement; "We have come to the conclusion that the classical laws of color mixing conceal great basic laws of color vision. There is a discrepancy between the conclusions that one would reach on the basis of the standard theory of color mixing and the results we obtain by studying the natural image." Although generally regarded as fascinating research by the physicists and the research community, these observations irritated, if not inflamed, the color vision community. Land stated in this first paper that Colorimetry was just a special case of color appearance.

(Insert Figure 1 near here)

The paper describes the matched camera and double projector used in the "red and white" demonstrations (Figure 1). It was designed by Dave Grey and built by the Optical Engineering Department at Polaroid. The camera used a single lens with a beam-splitting prism to produce two identical images of the scene, one above the other. Behind the prisms were holders for Wratten colored filters. The camera had a Polaroid roll filmback for Type 46L continuous tone black and white transparency film. The developed image, once dipped and dried, was placed between two pieces of lantern-slide glass and put in the projector. Because the two separations are on a single sheet of film, rotational adjustment for superposition is not required. One of the two independent projection lenses has screw adjustment for horizontal and vertical registration.

The single camera lens allowed two images without stereo parallax from a single exposure. The instant film and registration adjustments permitted a working time of 10 minutes from the click of the shutter to the evaluation of the projected image. These features were important factors in making good images, because red and white photography is particularly sensitive to loss of highlight and shadow detail.

The paper described 22 different experiments that report the color appearances of projections. The first 16 described the additive combinations of red and white light, red and white images, different hues and spectral distributions. The remaining experiments varied the proportions of spectral stimuli, but failed to display variegated colors. The paper described a dimensionless coordinate system and showed color correlated with the ratio of normalized radiance in each waveband. Of particular interest is the lack of variegated color sensations seen in positive/negative projections and single/double contrast projections. The positive-negative experiments used for example, a red positive image in red light projected in superposition on a red negative image in white light. The single-double contrast experiments used for example, a red positive image in red light projected in superposition on two red positive separations laminated together in white light. Although the negative/positive projections and the single/double contrast generated a wide range of relative red and white radiances, they did not generate the same variety of different colors as red and green separations.

Color Vision and the Natural Image Part II

[Land, Proceedings of National Academy, 1958][7]

This paper described an elegant double image monochromator made by Dave Grey and Stan Haskell. A pair of color-separation images were viewed in Maxwellian view with different illumination. The light collected from a grating was imaged on a black-and-white separation and relayed to the eye's pupil. Screw adjustments allowed precise image registration. The paper described extensive experiments reporting the color names observed with different spectral illumination.

The paper also describes the "Sodium Viewer". It was first demonstrated at the 1958 OSA meeting in Detroit. This large viewer combined red and green image separations with a semi-silvered mirror. One side used incandescent light and a yellow filter; the other side used a sodium street lamp. In superposition the two yellow images generated a range of colors from yellow to black. When viewed with a green filter, the screen generated a wide range of colors consistent with red and green projections. When viewed with a red filter the same display generated a reversed color version of the scene (red objects became green and green objects became red). The red and green filters, held in front of the eye reduced the intensity the narrow-band sodium light, but had no effect on hue. These filters modified the broadband tungsten yellow to either red, or green light. In one case, the green record in green light made a variegated positive image; in the other case the green record in red light made a variegated reversed color image.

Experiments in Color Vision

[Land, Scientific American, 1959][8]

This paper recounted and elaborated on the experiments in the National Academy papers. It was accompanied by a number of excellent color illustrations. The paper created a lot of interest in color research. In response to a great many letters to the editor Land provided more information about how to make the images and wrote an extensive reply to the letters.

Some Comments on Judd's Paper

[Land, J. opt. Soc. Am., 1960][9]

D. B. Judd wrote an article in JOSA listing numerous explanations of red and white photography.[10] They included color adaptation, recognizing the illuminant using highlights and memory color. Land wrote a short reply and performed additional experiments looking for the influence of Judd's hypotheses on red and white projection. He looked for changes of color appearance in projections lasting only 1/1000 seconds. He looked for changes in color in images taken with crossed polarizers to remove all highlights and visual clues to the spectral content of the illuminant. He looked for the influence of color memory by spray painting oranges and then photographing them. He found no evidence to support any of Judd's hypotheses as explanations of the colors seen in red and white projections.

Binocular Combinations of Projected Images

[Land and Daw, Science, 1962][11]

Land and Daw modified the procedure described in another Science article by Land and W. Hunt (Land's first scientific paper, 1936)[12]. Here they simultaneously compared the colors generated by the red image on one eye and the white image on the other eye, with the combined image on both eyes. Although the colors from binocular combination in the cortex are correctly identified, they are not the same as those generated by the combination of both red and white images on both retinas.

Colour in the Natural Image

[Land, Proceedings of the Royal Institution, 1962][13]

This was the first of two Land Friday Evening Discourses given at the Royal Institution. It integrates the wide range of red and white experiments and the dimensionless coordinate system. In the summary, Land described his first experiments using real papers illuminated with the projectors used for red and white photography. These projectors, with a blank slides in the film holders, and a red projection filter in one / a green projection filter in the other, anticipated the Mondrian experiments of the later sixties. These experiments were the basis of the idea that color appearance is determined by the apparent lightness in each waveband, an idea that was developed further in Retinex papers.

Colors Seen in a Flash of Light

[Land and Daw, Science, 1962][14]

This paper cites Thomas Young's report that everything was visible in a room illuminated by a flash of light made with a Leyden jar. Land asked his old friend Harold Edgerton to make a flash lamp to replace the incandescent lamp in the double projector. This generated one-millisecond projected images. Other experiments described in this paper used one-microsecond flashes. The mechanism responsible for red and white projections shows no sensitivity to the duration of the stimulus. Temporal adaptation does not play a role.

Why After-Images Are Not Seen In Normal Circumstances

[Daw, Nature, 1962][15]

In this paper Nigel Daw formed a colored after-image by having observers stare at a fixation point in a two-color projection for several minutes. The after-image was seen clearly when viewing a blank, white projection screen. In Daw's experiment he viewed the after-image using a color separation image in white light. Daw asked the observers to maintain their fixation point - they reported colored afterimages. When asked to change their fixation point - they reported that the after-image disappeared. When asked to return their fixation to the original point - they reported that the afterimage reappeared. After-images are suppressed if the spatial pattern of the afterimage does not superimpose with the current image.

Following the experiments using real papers in the 1962 Royal Institution paper, Land concentrated on experiments using real papers. The first displays used recognizable shapes such as animals, later Mondrians used many different size and shape rectangles. The important idea is that the pattern of afterimages is not superimposed with the stimulus image, following Daw's experiments. This is a very important fact about experiments studying complex images. In real scenes there are very few objects that have the same size and shape retinal images. The probability of transferring the afterimage of a previous image to the current object of interest is small.

For regular arrays of squares and rectangles, used frequently in standard test targets, the opposite is true. Here, the spatial shape of the afterimage fits the present image and the afterimage is combined with the present image. Despite Land's discussion of avoiding afterimages in experimental display design, regular arrays are frequently used in today's experiments. It is most unfortunate when these displays are called Mondrians, completely missing the point.

Visual Response to Gradients of Varying Colour and Equal Luminance
[Nature, 1964][16]
These experiments studied the appearance of a Mach band on continuous and step chromaticity gradients having equal luminance. It found that all observers reported chromatic Mach bands in steps, but only half of the observers saw them in continuous gradient.

RODS AS COLOR RECEPTORS

One of the many experiments using Mondrians and controlled illumination used an incandescent lamp plugged into a Variac. By rotating the dial, the voltage, and lamp luminance were adjusted. The experiment was to reduce the amount of light until the Mondrian appeared colorless. At first, the Mondrian went from colored to invisible, without the expected colorless scotopic image. We assumed that we must be above rod threshold, so we sat in the dark and repeated the experiment twenty minutes later. Again, the Mondrian went from colored to invisible. After two hours of dark adaptation the result was the same. As soon as the Mondrian was visible in the dark room it appeared colored. The expected colorless rod image never appeared in this experiment. The reduction of voltage caused a dramatic change in color temperature of the illumination. The following papers describe experiments measuring rod and cone visual thresholds and color appearances.

Interactions of the Long-Wave Cones and the Rods to Produce Color Sensations
[McCann and Benton, J. opt. Soc. Am. 1969][17]
This paper was the first in a series that documented the fact that rods are a perfectly good color receptor. First, this paper used three narrow-band illuminants to illuminate colored Mondrians; second it performed classical dark adaptation threshold measurements to plot the recovery of sensitivity following exposure to bright, white light. The dark adaptation curves for 656-nm light showed only the relatively insensitive cone recovery curve. Both the 546-nm and 450-nm dark-adaptation curves show a fast cone recovery, and after 8 minutes, showed a further increase in sensitivity due to rod recovery. The break in these curves provided an accurate measure of radiance at each wavelength for minimum cone threshold. The experiments then showed that a very colorful Mondrian was seen by the combinations of a monochromatic long-wave cone record in 656 nm light and a an apparently colorless, 546 nm rod record 100 times below M- and S-cone threshold.

One of the more interesting aspects of this paper was the comparison of colors seen with rod with those seen by the cones. Are they different? These experiments used two multiple image monochromators[7], one for each eye. Both devices had identical pairs of black-and-white color separation photographs taken through red and green filters. One eye saw a rod-cone color image, while the other saw a cone-cone color image. The monochromator knob allowed the observer to adjust the wavelength of the light illuminating the green, or short-wave record. When viewing real colored papers and varying the wavelength of illumination, the scene changed because the papers had different reflectances for each wavelength. By using black-and-white photographic records and changing the wavelength, the scene remained constant. This allowed the experiment to study the effect of illumination wavelength independently.

When the radiance was below cone threshold, the image was colorless. Changing wavelength made the image brighter or darker, without any hint of color. When a red, or long-wave record was added in 656-nm light the image had many different colored areas. Now changing the wavelength of the short-wave separation illumination did not change the colors, just the apparent brightness of the short record. With constant photographic separations the colors from rod-cone interactions are constant, particularly when the radiance of the green-separation illumination is adjusted for scotopic sensitivity.

(Insert Figure 2 near here)

Figure 2 illustrates this result. On the left there are the observations from three combinations below M and S cone thresholds. The first example shows that the colors red, yellow, blue green and gray are observed with 650 nm illuminating the long record and 550 nm illuminating the short record. The effect of changing the short wave illumination from 550 nm to 500 nm makes that image brighter. After adjusting the radiance of the 656 nm illumination the colors are the same as those seen using 656 nm and 550 nm illumination. The effect of changing the short wave illumination from 500 nm to 450 nm makes that image more dim. After adjusting the radiance of the 656 nm illumination the colors are the same as those seen using 656 nm and 500 nm illumination. Although wavelength controls the apparent brightness of the short-wave record, it has no effect on the set of colors observed. Observers see a constant set of colors below M- and S-cone threshold, regardless of the wavelength illuminating the short-wave record.

Figure 2 (right) shows the colors observed with the same records at higher radiances. When all stimuli were above L-, M-, S-cone thresholds, then changing the wavelength of the illumination changed the sets of colors. With 656 nm and 550 nm illumination observers reported reds, yellows, greens and dark blues. With 656 nm and 500 nm observers reported reds, yellows, blue greens and grays. With 656 nm and 450 nm observers reported reds, blues and magentas.

The experiment asked observers to alternate eyes to compare rod-cone colors with cone - cone colors. The cone-cone eye viewed identical images except for radiance levels. A second image monochromator illuminated identical photographs. Here the green separation image was just above cone threshold. Here turning the wavelength changed the colored wash of the green separation. At 540 it was green, at 500—cyan, 450—blue, and 420— violet. When combined with the red separation image, the multicolor image changed colors with green record wavelength. The experiment asked if there was a color that generated the same set of colors from rod-cone interactions as from cone-cone interactions. The answer was yes and the above-cone-threshold wavelength was 495 ±4 nm matched with only a small difference in apparent brightness and color saturation.

Rod-Cone Interactions: Different Color Sensations from Identical Stimuli
[McCann, Science, 1972][18]

This paper used a display drawn by Jeanne Benton at Edwin Land's request. It was a street scene with a red door on one side and a green awning in the other. A gradient in long-wave illumination provided more illumination to the less reflective awning, and less illumination to the highly reflective door. An opposite gradient in middle-wave illumination provided less illumination to the highly reflective awning, and more illumination to the more reflective awning. When properly adjusted, the awning and the door sent identical long- and middle-wave radiances to the eye. Land's photopic experiment showed that red and green areas in the same scene were generated by identical stimuli.

By controlling the wavelengths and radiances of illumination the middle-wave light could be below cone threshold and be seen only by the rods. The awning appeared light and the door appeared dark, despite the fact that the radiances were identical. In the image that stimulated the long-wave cones the door appeared light and the awning appeared dark when they had identical long-wave radiances. The hypothesis tested here was whether identical physical stimuli for rods and identical stimuli for cones would generate identical sensations. Land's Retinex hypothesis suggested that the cones acted as independent channels to generate independent lightness images. The question here was whether images produced by physiologically independent systems, namely rod and cones, combine quanta catches or combine lightnesses to generate color. The results were consistent with color as a function of apparent lightness generated by independent channels.

Color Vision from Rod and Long-wave Interactions:
Conditions in which Rods Contribute to Multicolored Images
[McKee, McCann and Benton, Vision Research, 1977][19]
This paper presented additional evidence showing that rods participate in generating multicolored images. Unlike the earlier experiments that identified receptor responses for the component images viewed alone, these experiments measured rod and cone properties in the combined color images. Here, we used traditional criteria for distinguishing rod and cone responses (action spectra, Stiles-Crawford effect, luminance level relative to absolute threshold) to show that the rods were one of the two receptors responsible for the multicolored images at low light levels.

The stimuli for these experiments were the color separation images described above — transparent slides of the same scene taken through a red or a green filter. These transparencies were mounted in two separate beams of a double monochromator. The "red" transparency was illuminated by monochromatic light of 656-nm set just above threshold. The observer was asked to increase the intensity of the light illuminating the "green" transparency until she could just see sensations of many colors. The experimenter varied the wavelength of the light. The resulting action spectrum matched the scotopic luminosity curve. In a second experiment, the intensity of the 656-nm light illuminating the "red" transparency was increased by about 1 log unit; the observer was asked to increase the intensity of the light illuminating the "green" transparency until they could just see the best balance of colors. Again, the experimenter varied the wavelength of the light, and again, the action spectrum matched the scotopic luminosity curve.

Additional action spectra that produced the best balance of colors were measured at increasing intensities of the light illuminating the "red" transparency. For four different intensities of "red illumination" the measured action spectra fit the scotopic luminosity curve,[19] indicating rod only response. At higher intensities the action spectra broadened to indicate cone responses to the green separation image. The adjustments generated scotopic action spectra at low intensities showing rod-cone color, and photopic action spectra at higher intensities showing cone-cone color.

In another experiment, we used the Stiles-Crawford effect to demonstrate that the rods contribute to color experience. The rods have essentially the same sensitivity as a function of pupil position, while the cones have markedly different sensitivity. For this experiment, the 'red' transparency was again illuminated by 656 nm, and the 'green' transparency was illuminated by 510 nm. The observer adjusted the intensity of the 510 nm beam to produce the best color balance. Instead of varying the wavelength of light illuminating the 'green' transparency, the experimenter varied the position of the image in the plane of the observer's pupil. At low intensities of the 656 nm image, the amount of light in the 510 nm beam required to produce color balance was independent of the position in the observer's pupil, indicating that the multicolored experience was dependent on rod input. At high intensities, the amount of light required for color balance changed with pupil position, the characteristic property of cone vision.

Variegated Color Sensations from Rod-Cone Interactions: Flicker-fusion Experiments
[Benton and McCann, J. opt. Soc. Am. 1977][20]
This paper used flicker fusion frequency as the signature of cone activity. Here again variegated color images were observed well below middle- and short-wave cone activity. Just as with the other experiments above, the physiologically distinct rod receptors act as a set to form an image in terms of lightness. Flicker-fusion rate is fundamentally related to the temporal response of the rods. It is much lower that that of the cones. When observers were asked to adjust for minimum flicker in the color image at low radiances they

produced a flicker curve characteristic of rod activity. These experiments support the idea that independent lightnesses formed by physiologically distinct receptor sets generate color.

DISCUSSION

One of the remarkable things about red and white photography is the wide range of colors observed compared to those found in complementary color shadow experiments. The fact that whites and yellows as well as blues and blue greens were observed in the same scene. As described above Land and Daw performed many different experiments to rule out object memory and other cognitive explanations.

(Insert Figure 3 near here)

One of the most interesting objects is the blue paper cup shown in Figure 3. Land's original slide has been scanned to show the red and green separations. Figure 4 plots the spectral distribution of 3200 degree Kelvin tungsten light as modified by the Wratten 26 red and 0.4 Wratten 96 filters.

(Insert Figure 4 near here)
(Insert Table 1 near here)

Table 1 shows the summed areas under the 1964 X, Y, Z sensitivities[21] for both the long-record red light and the short record white light. The red light had X = 584.3, Y = 280.4 and Z = 0.0. The white light had X = 580.7, Y = 542.3 and Z=204.7. When combined on the screen the X image on the retina was composed of half long-wave record and half short-wave record. The Y image was 34% long-wave record and 66% short-wave record. The z image was 100% short-wave record.

(Insert Figure 5 near here)

Figure 5 shows the combined images using the proportions calculated in Table 1. These images are illustrations of the spatial information captured by the retinal response function of the eye. These images show the combinational degradation of color separation images captured on film. These images are created by the physical response functions of vision. These combination show effects on the appearance of objects, but do not involve adaptation processes or cognitive functions. They are simply the result of the sensitivity function of vision. Although this is the most proximal process, namely the response of cone pigments, it can provide an explanation of the blue cup in the picnic scene. By comparing the X, Y, Z separation images we see that the Z separation is equal to the original green separation because Z is insensitive to long wave light. The Y separation has a darker cup because it is 35% red separation. The X separation is the darkest because it is 50% red separation. As previously described, blue objects are lighter in the short-wave Retinal Response Image than in the others. Thus, the physical properties of retinal response are consistent with color seen in Red and White projections. The above calculations are similar to photographs made using film-filter sensitivity curves matching cone pigment sensitivities.[22]

SUMMARY

The equipment used in these experiments, although somewhat unique forty years ago is becoming more unusual in the modern world of digital displays. Nevertheless, the experiments described and seen here are important visual experiments. Using this equipment with photographs and real papers we were able to control the image separations far better than we can in today's digital display systems. The more important point is that these experiments provide compelling evidence that the fundamental mechanism of color is spatial in nature. Color constancy illustrates the independence from quanta catch. Experiments probing the role of adaptation as the mechanism underlying color constancy always indicate that the adaptation hypothesis is wrong.[23-25] Colors seen in red and white and in rod-cone interactions were designed as probes of our visual system and they are an important part of visual research history.

Land's "outrageous" observation that "Colorimetry was just a special case of color appearance" seems a much more mellow and more accurate statement today.

ACKNOWLEDGMENTS

The original work was possible because of the leadership of Edwin Land and Nigel Daw, the help of countless people associated with Polaroid's Vision Laboratory and the support of Polaroid Research.

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BIOGRAPHIES

John McCann received his B.A. degree in Biology from Harvard University in 1964. He managed the Vision Research Laboratory at Polaroid from 1961 to 1996. His work concentrated on research in human color vision, large format instant photography and the reproduction of fine art. He is a Fellow of the IS&T. He is a past President of IS&T and the Artists Foundation, Boston. In 2003, he received the IS&T /OSA Edwin Land Medal. He is currently consulting and continuing his research on color vision.

Other biographies to follow

Figure 1. Diagrams of the matched double camera and projector. The camera used Wratten 24 (red) and Wratten 58 (green) filters behind the prism and in front of the film. The projector used Wratten 26 (red) and Wratten 96 (neutral density) 0.4. The range of color sensations is larger with red and white, than with red and green projection filters.

Figure 2. Diagram of observer reports of colors seen in different displays. Three pairs of wavelengths (656 & 550, 656 & 500, 656 & 450) were use at two different radiance levels. The left half of the diagram reports the constant set of colors below M- and S- cone thresholds. The right shows variable sets of colors when the stimuli are above threshold for all cone types. The sets of colors using 656 and 500 nm are the same above and below M- and S-cone thresholds.

Figure 3. Color separation of Land's Picnic slide. The paper cup the right, behind the hard-boiled egg, has a pastel blue color that is difficult to explain using complementary color hypotheses. The left image is the red separation and the right image is the green separation. Note the maraschino cherries in the jar are green. They are lighter on the right than on the left.

Figure 4. Spectra of red and white illuminants projected on the screen.

Table 1. Tristimulus values of red and white illuminants made by integrating the 1964 CIE X, Y, Z sensitivity functions over the illuminant spectra. The table also shows the percent maximum contribution of each Tristimulus Value and each record.

Figure 5. Separation images as combined by the X, Y, Z broadband sensitivities functions. The photographic separation images are on the left; The X, Y, Z separations on the right. The X image is 50% long- and 50% short-wave separation. The Y image is 34% long- and 66% short-wave separation. The Z image is 100% short-wave separation.

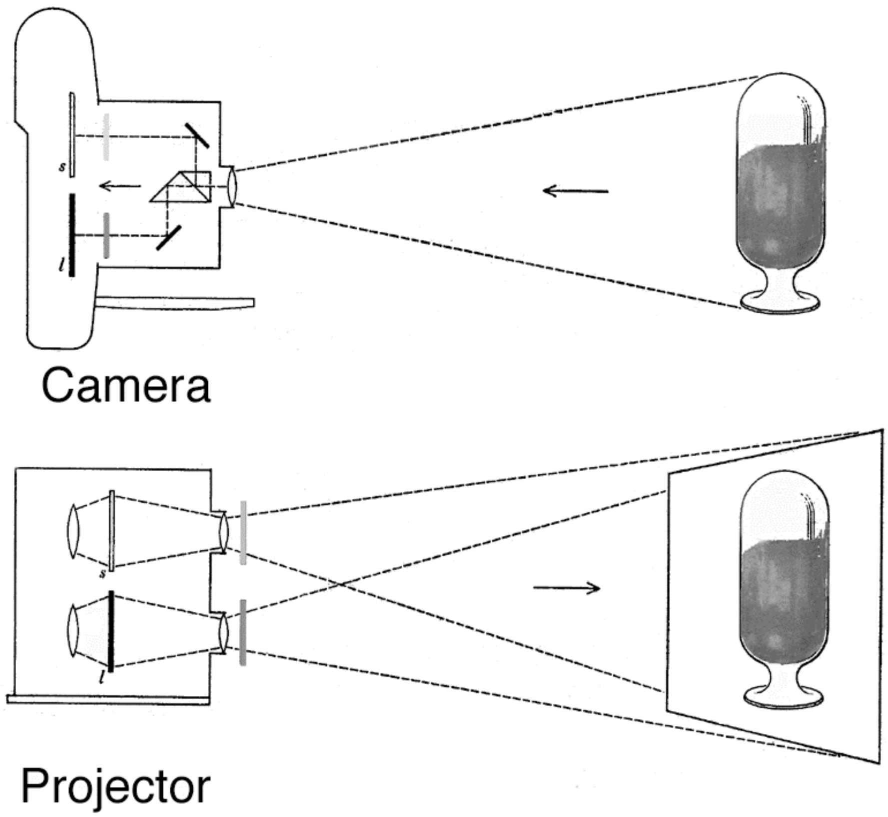

Figure 1

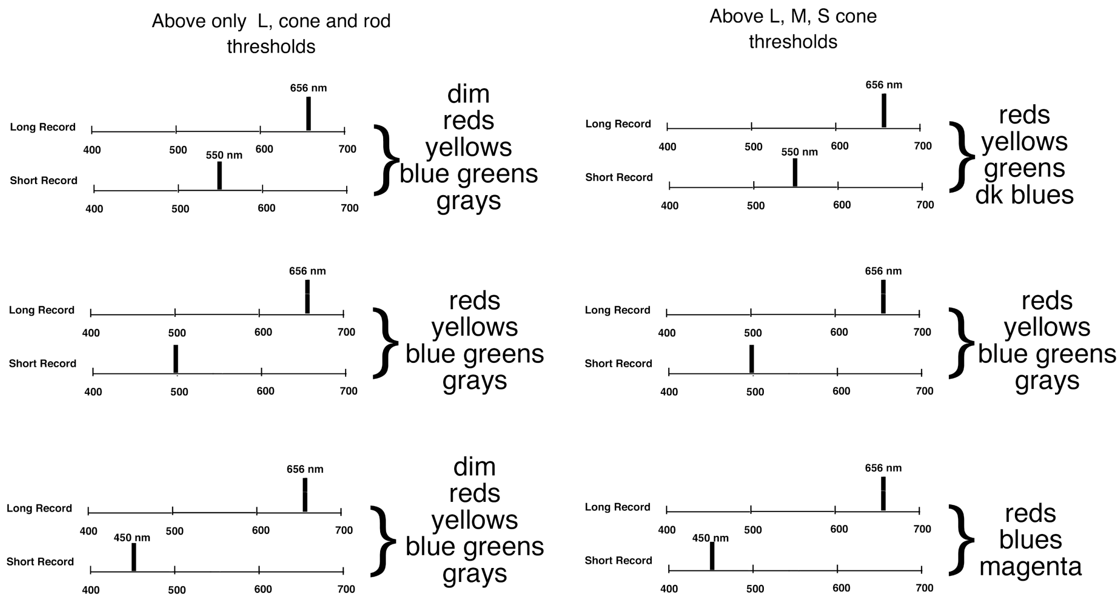

Figure 2

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Figure 3

(Editor please note This was designed as a two column figure. If you have to put it in one column then it should be cut into left half and right half and placed one above the other.)

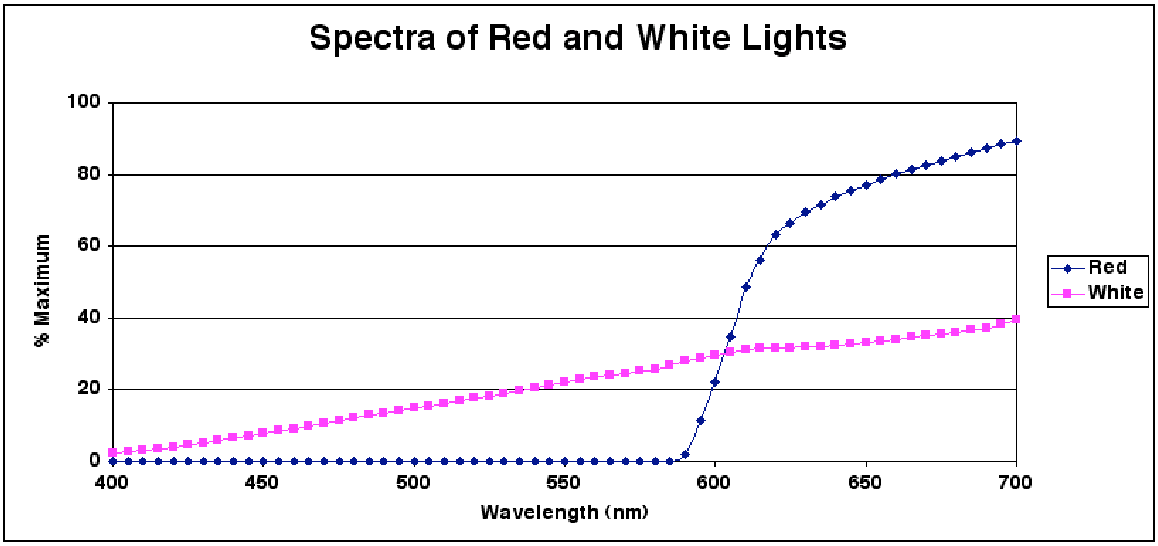
Spectra of Red and White Lights
100
80
60
40
20
0
% Maximum
400
450
500
550
600
650
700
Wavelength (nm)
Red
White

Figure 4

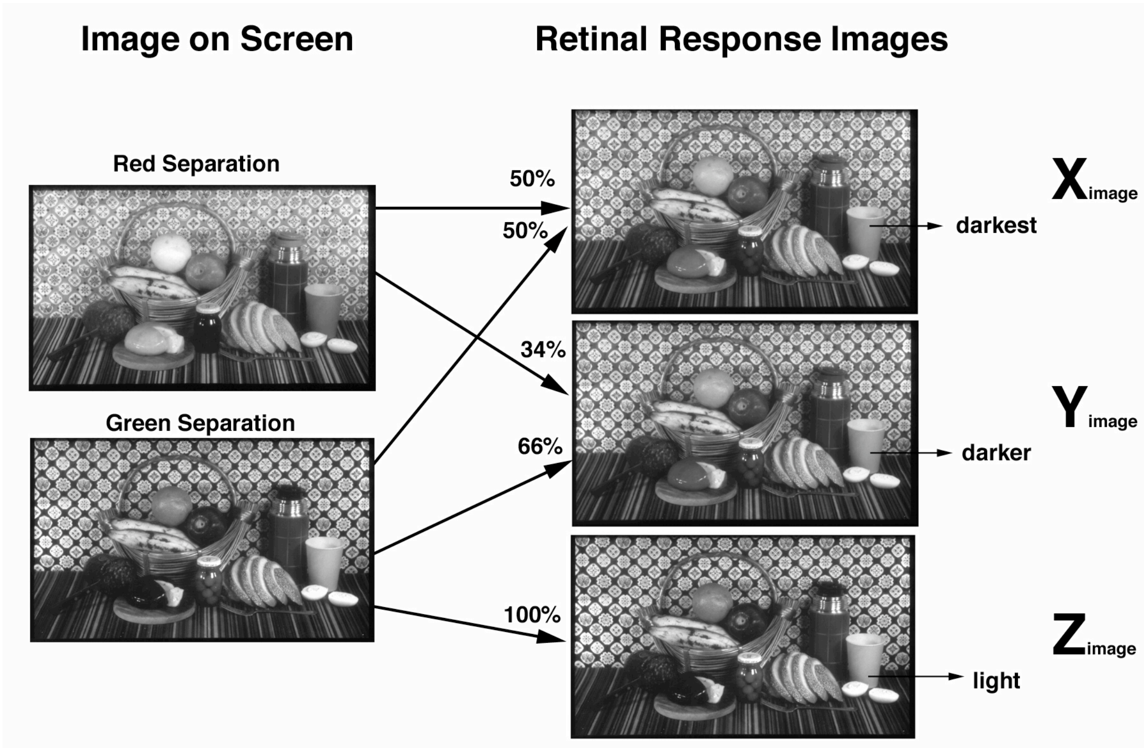

Figure 5

(Editor please note This was designed as a two column figure. This cannot be split into two parts.)

	X	Y	Z
Long Record	584.3	280.4	0.0
Short Record	580.7	542.3	204.7
Total	1165.0	822.7	204.7

	X	Y	Z
% Long Record	50%	34%	0%
% Short Record	50%	66%	100%

Table 1

Photo of J. McCann

Other authors to follow