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Appearance at the low-radiance end of HDR vision: Achromatic & Chromatic

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

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

Abstract

Human vision spans more than 10 log units of dynamic range of light response. That is the ratio of the radiances from snow on the top of a high mountain to the amount needed for dark adapted humans to see a light. That range is possible because of two types of retinal cells; rods (high sensitivity) and cones (daylight vision). There are many familiar spatial experiments in which equal local stimuli make unequal appearances in daylight. This paper tests whether Simultaneous Contrast, Adelson's Tower, White's Effect, Checkerboard and Dungeon Illusions, Benary's Cross, Color Contrast and Color Assimilation behave the same using rod vision. Since these experiments are the result of spatial processes, it is possible that the different anatomy and physiology of rods and cones could limit the range of these effects. Remarkably, spatial effects at the lowest end of our visual HDR range are very similar to those at the top of the range in sunlight. Different physiological systems, with different size receptive fields, generate similar spatial interactions.

Introduction

Imagine we take a colored test target, such as a Munsell ColorChecker® into a deep winding light-free cave. As we walk further and further into the cave, the radiance of the black paper will decrease to approach zero. If we go slowly into that cave we will dark adapt, because our rod and cone retinal sensors will become more sensitive to light. The cones reach their asymptotic limit of sensitivity after 8 minutes in the dark, while the rods reach our vision's absolute limit after 30 minutes in the complete absence of light. If we move back toward the entrance of the cave we will go from no light to detection threshold. At rod absolute threshold we can detect a flash of 4 to 6 photons (Hecht et al. 1938). We cannot see any objects; all we can do is detect the presence of light. Increasing the illumination does two things: it allows us to see ill-defined forms, or colorless shapes, and it causes rod vision to light adapt, thus raising detection threshold. Unlike film with fixed sensitivity to light, vision both *dark adapts* to gain sensitivity, and *light adapts* to lose it (Dowling, 1987). Further increases in illumination makes shapes clearer, and then sharper, and then colorful, and then bright, and then dazzling. The other end of the 10 log unit range is snow on top of a mountain.

Light adaptation, caused by bleached photopigment, sends a signal out of the retina until the rods and cones have regenerated all the bleached photopigment (Alpern & Campbell, 1963). Exposure to light creates a light-adapted floor that determines the minimum detectable stimulus at that moment.

Mountaintop snow bleaches so much photopigment that it takes more than 30 minutes in total darkness to approach absolute threshold again. Just because the eye can detect light over this 10 log unit range, does not mean that we can see details in a particular scene over that range. Dark Adaptation is a slow chemical process that follows the regeneration of rhodopsin in the pigment epithelium and re-migration back into the rod outer segments. Light Adaptation is a fast neural process that is a different mechanism. Light and dark adaptation have very different rates of losing and regaining sensitivity. It is not a simple reciprocal mechanism. As well, pupil size has an asymmetric response to light and dark, with fast and slow responses. The complex balance of pupil size, light, and dark adaptation is scene dependent, and sets the floor of the range limits of what we see at a given moment.

This paper studies what we see near absolute threshold, rod vision and the low radiance end of human HDR vision. In particular, it looks for changes in the way we process spatial information. Such changes are possible because of the many differences in anatomy and physiology of rods and cones. These differences can be measured in the comparisons of resolution limits and spatial frequency responses for rods and cones.

Appearance at low light levels

Our everyday life takes place at high light levels. We work at daylight, or near daylight luminances. We are all familiar with many interesting spatial phenomena caused by our visual system. In these phenomena, areas with equal radiances look different. In Simultaneous Contrast two identical light meter readings have two different appearances. In Assimilation experiments, gray test patches appear different, but the direction of change is opposite to that of Simultaneous Contrast.

This paper looks at appearances at very low light levels. Do we see Assimilation, and Simultaneous Contrast with rod-only vision near absolute threshold? Our rod-only vision is unusual in that it behaves as a black-and-white film. It renders the multicolored world in achromatic lightnesses. It has many physiological properties that are distinct from those of cones (Davson, 1962). Rods have low-resolution and have large spatial pools to increase sensitivity. They make up almost all of the far periphery, but are not found in the fovea. They are wired in a different manner than cones, and have different time constants. Are appearances the same with rods, as cones, using the equivalent of a different hardware system?

Familiar spatial achromatic targets

Table 1 shows six familiar test targets that contain pairs of identical middle-gray areas:

- Simultaneous Contrast - gray lighter in black
- Adelson Tower - gray lighter in shade [B].
- Whites Effect Assimilation - gray lighter next to white
- Devalois' Checkerboard - gray lighter next to white
- Dungeon Illusion - gray lighter next to white
- Benary Cross - gray lighter when perceptually "in" white.

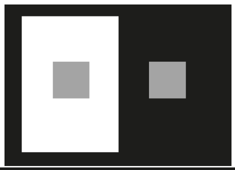
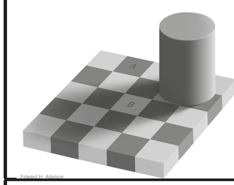
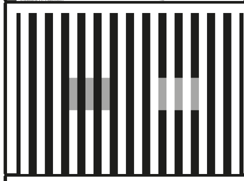
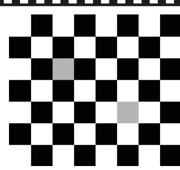
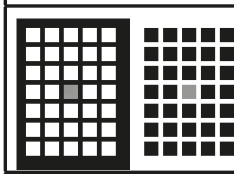
	Name	Lighter on Rods	Lighter on Cones
	Simultaneous Contrast	Right	Right
	Adelson's Tower	Right	Right
	White's Effect	Right	Right
	Devalois Checkerboard	Right	Right
	Dungeon Illusion	Right	Right
	Benary's Cross	Right	Right

Table 1. Six examples of human spatial image processing. "Lighter on Rods" identifies whether observers saw the left, or right gray area as lighter for rod vision. "Lighter on Cones" report results in sunlight.

We are familiar with these phenomena when viewed above cone threshold. When these spatial targets are viewed in daylight, human vision transforms equal scene radiances into different appearances. In this paper, we view these targets at the lower extreme of the human HDR range. When viewed with rods alone, do they behave: the same, almost the same, or differently, near the absolute threshold of vision?

Methods

All experiments were conducted in the middle of the night in a room without illumination, and with shaded windows. Four observers were dark adapted a minimum of 1 hour before making observations. The light source was a single white LED at a distance of 20 feet. Observers had their backs to the light and held a printed test target paper (at 16 inches) so that nearly uniform light passed over their shoulder onto the paper target. In this part of the experiment they looked at six achromatic targets (Table 1). Each observer repeated the task four times in different trials.

Control experiment for rod vision

We used three controls to insure the lightness judgements were being made using rod vision. All six achromatic targets, each on a separate piece of paper, had a strip of cyan, green, yellow, and red color patches printed on the top border of the page. Observers were asked to describe the appearance of the top patches. If the light was above cone threshold the observers would report that they saw different colors. If the light stimulated the rods alone, then they would see a gray stair-step-wedge that was lightest on the left and darkest on the right (cyan to red). The colors were chosen to follow the scotopic luminosity curve.

The second control for rod vision was a small black dot in the center of a white paper. The dot subtended 12 minutes of arc, when viewed at 16 inches. Each observer was asked to look for the dot. Since the dot was much smaller than the fovea, and since there are no rods in the fovea, the dot is invisible near the absolute threshold of vision. If cones are active, the dot is clearly visible.

The third control experiment used 4 targets with high-contrast square-wave gratings. Each subtended 10° by 10°. The largest had black lines of 12 minutes of arc, or 24' per cycle, or 2.5 cycles per degree. Each succeeding square-wave grating had the same size and half the square-wave frequency. The finest grating was 20 cycles/degree. Some were horizontal, others were vertical. Near absolute threshold all gratings will be below resolution threshold. With increasing scotopic luminance, low-frequency gratings become visible before high-frequency gratings (Savoy, 1978). All gratings were clearly visible above cone threshold.

We used these three tests to verify that the observations of the six targets were made using rod, or scotopic vision. In each trial, each observer reported: seeing a gray step gradient, not colors; not able to see the dot; and uniform gray squares, not gratings.

Relative Apparent Lightness - Rod Vision

The principle experiment was to ask observers to identify the lighter of the two gray areas. The experimenter gave the observer a stack of paper test targets to view at 18 inches. Each target was rotated 180°, half the time. The observers' task was to rotate the paper with the printed page so that the lighter gray was on the right. In any experiment, roughly half of the pages were rotated 180°. The observers went through the stack of six achromatic test targets. Later, the experimenter tabulated the results for rod vision. All observers, in all trials, reported the same result for rod only vision. In Table 1 the targets are arranged so that the right test gray was lighter than the one on the left (Lighter on Rods).

Relative Apparent Lightness - Cone Vision

The following day in daylight the observer performed the same task using cone vision. We used the same targets, this time in sunlight. The same procedure was repeated four times. The luminance of the white paper, measured by a Minolta CS-100 meter was 14,600 cd/m^2 (x=0.32, y=0.33). The result are tabulated in Table 1 (Lighter on Cones).

Above cone threshold, all observers reported the same result for these six test targets, for all trials. These targets do not show variable appearance with different observers, and different trials. All observers reported that the relative magnitude of the change in lightness was "about the same" in rod and in cone vision.

Achromatic Spatial Results - Rod vs. Cone vision

In this simple relative lightness comparison we observed the same lightness phenomena using rods, as using cones. All the examples shown in Table 1 had the same direction of lightness change using rods, as seeing with cones. All observers reported that the apparent changes in lightness were "about the same". The result is interesting because the rods have such different anatomy and physiology compared to cones.

Rod/Lcone Color

In the second phase, we studied chromatic targets near the absolute sensitivity threshold. Again, we used illumination that was so dim that it stimulated only the rods just above their absolute threshold.

In order to make a colored image we have a minimum set of requirements:

- two independent sets of information;
- two different bands of wavelengths for that information;
- two independent retinal receptors, with different spectral sensitivities (such as: rods, L, M, S cones).

The information can be from colored papers in daylight illumination, or achromatic color separation information sent to independent color channels of printers or displays.

Working backwards from retina to the illumination, we need two different retinal receptors with different spectral sensitivities. The rods have the highest sensitivity. To see colors with the least amount of light, at the lowest end of the human HDR range, we should use the rods as one of the two receptors. Historically rod vision has been studied using daylight spectra, or other very broad band light. As well, rod vision has been studied using very narrow band light. Under these conditions rod vision appears achromatic.

Stabell (1967, 1998) found colors from the interactions of rods with cones. McCann and Benton (1969) used low-voltage tungsten light that emitted much more long-wave, than short-wave light. They observed the wide range of colors expected for two-color vision. They verified that these colors were the result of rod/L-cone interaction with experiments using rod vs. cone physiological properties. McCann, et al. (2004) reviewed these experiments that included:

- dark adaptation curves
- measured action spectra- photopic/scotopic
- Stiles-Crawford Effect
- flicker fusion frequency
- apparent sharpness

Colors generated by the least amount of light will use the rods to detect the shorter-wave light, and L-cones to detect long-wave light. Colors are best with the right balance of long-wave to short-wave light (McKee, et al. 1977). In order to balance the much greater rod sensitivity, we need minimal short-wave light. As well, we need much more long-wave light to balance the L-cones insensitivity. Firelight, a 2,000°K blackbody radiator, has the desired balance of spectral light (McCann, 2006).

Control experiment for rod/ L-cone color vision

We used prints of Figure 1 (left) for identifying rod/L-cone vision. The left side shows the color test target with green and blue letters.

These letters were selected to have the same average scotopic reflectance. When viewed in firelight all letters appear cyan when the target is at 20 feet from the candle flame (Figure 2 right). However, if it is held very close to the flame (1 foot), so that there is enough firelight to stimulate all the cones, the observers see distinct blue and green letters. We can use this control experiment to insure that we have viewing conditions that excite only rods and L-cones.

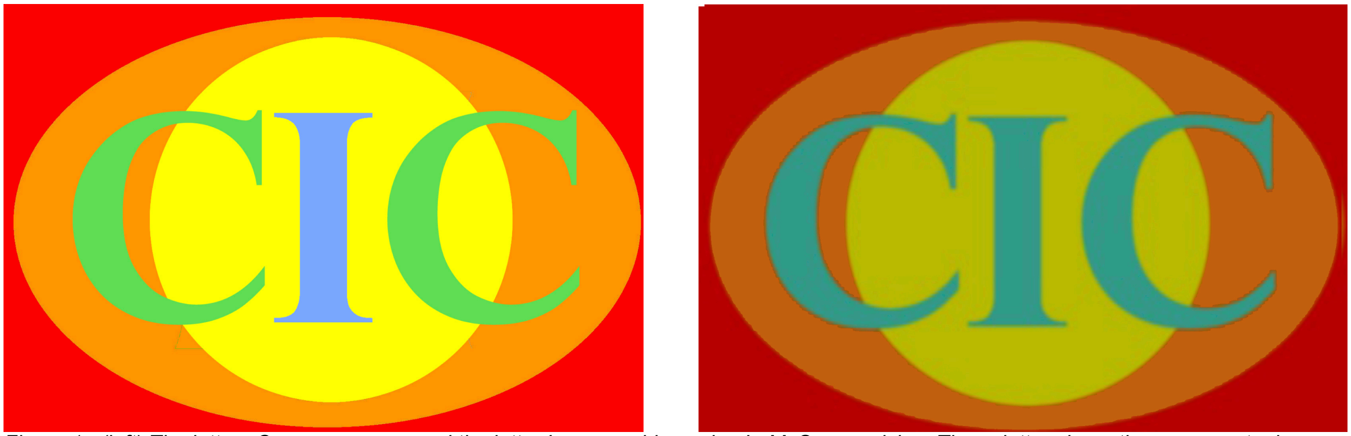


Figure 1. (left) The letters C appear green, and the letter I appears blue using L, M, S cone vision. These letters have the same scotopic reflectance for rod vision. (right) When viewed with a candle, at a distance, they appear the same cyan color with rod and L-cone interactions.

Familiar spatial chromatic targets

Table 2 shows two familiar test targets that contain pairs of identical areas:

- Simultaneous Contrast -
- Assimilation -

Color vision transforms equal scene radiances into different colors in these examples. These experiments view them at the lower extreme of the color HDR range. We are familiar with these phenomena when viewed above LMS cone thresholds. Do we see Color Contrast and Color Assimilation when viewed with rods for one spectral channel of short-wave light, and L cones for long-wave light?

Methods

All experiments were conducted in the middle of the night in a room without illumination and with shaded windows. The light source was a single wax candle at a distance of 20 feet. Again, observers had their backs to the light and held a printed test target paper (distance 16 inches) so that nearly uniform light passed over their shoulders onto the paper target. In this part of the experiment they looked at two colored targets (Table 2).

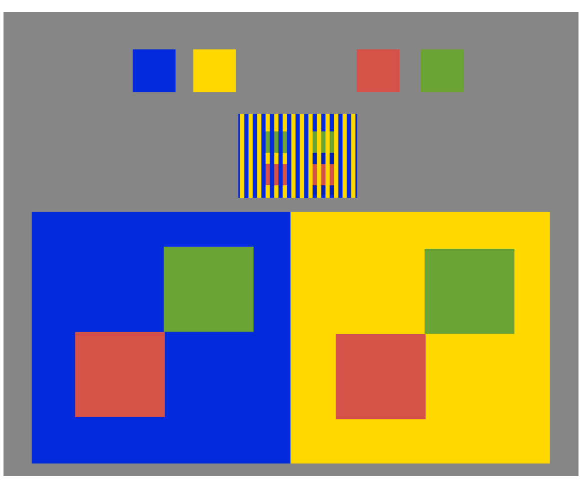
Target	Name	More Yellow on Rods/L-Cone	More Yellow on LMS Cones
	Colors Used		
	Assimilation	Right	Right
	Simultaneous Contrast	Left	Left

***Table 2**. Examples of human color spatial image processing.*

The top row in Table 2 shows the 4 colors used in these displays. Blue and yellow were background colors. Red and green were central test colors. Color Contrast works well with large angular subtends, while Color Assimilation works best with very small visual angles.

The second row of Table 2 divides the background and target into narrow blue and yellow stripes. The green test stripes are above the red test stripes. Observers report large changes in color. The top green stripes appear more blue on the left, and more yellow on the right. The lower red stripes are also more yellow on the right.

The third row of Table 2 uses large solid background areas and test areas. The green squares are above the red squares. Observers report small changes in color. The top green square appears slightly more yellow on the left, and slightly more blue on the right. The red square is also slightly more yellow on the left.

The Assimilation Target causes a large shift towards more yellow on the right, while Simultaneous Contrast causes a small shifts towards yellow on the left for both red and green test areas.

In Table 2 "More Yellow on Rods" column reports the position of appearances with more yellow in both the red and in the green test areas. For Assimilation with rod/L-cone color stripes were more yellow on the right for both red and green test colors. The same was true for L, M, S cone vision.

For Contrast observers reported more yellow on the left with both rod/L-cone color and L, M, S cone color.

All observers, in all trials, reported that these targets behaved: "almost the same" for both viewing conditions.

Color Results - Rod/L-cone vs. L,M,S cone vision

We found that color vision has consistent spatial behavior near absolute threshold and in bright sunlight. Other of our control experiments indicate consistent behavior over the entire range. All of the tested spatial demonstrations gave "almost the same" observer responses over the HDR range of illumination. There were considerable changes in apparent sharpness associated with retinal inhomogeneity. Our control experiments, used to identify rod vision, are good examples. Small dots and high-frequency square wave gratings are not detected. There were changes in color hue due to changes in spectral sensitivity. However, the spatial comparison process was remarkably constant, despite the well known changes in the anatomy and physiology of rods and cones.

Color and lightness appearances that controlled by spatial interactions at the lowest end of our visual HDR range are very similar to those at the top of the range in sunlight. This is true for both achromatic and chromatic targets.

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Author Biography

John McCann was an organizer and the Program Chair of the First Color Imaging Conference. He has worked on Color Constancy, Image Processing and HDR imaging. He has the Certificate of Commendation of SID. He is Fellow and Past-President, and Honorary Member of IS&T, OSA Fellow and Land Medalist of IS&T/OSA.