Color Vision 3:

Perceiving Environmental Surface Colors

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13 Feb, 2004

2 Important Color Vision Capabilities

Surface colors**:** *A principal function of color vision is for perceiving object materials. Moreover, many surface colors are not found in the rainbow or in any patterns of wavelength per se. Why? What else could be involved?*

***Color constancy* & its relatives:**

a) *Perceived colors typically remain stable under large changes in the spectrum of the illuminant—even though the wavelengths reflected by a given surface may be very different. How is this possible?*

b) *Color illusions, where local image patches with identical wavelengths have different perceived colors—due to changes in the illumination spectrum and changes in neighboring colors.*

c) *Land's experiments and a class demonstration.*

d) *Brainard et al. (2000): Stability of perceived colors under individual differences in L- & M-cones.*

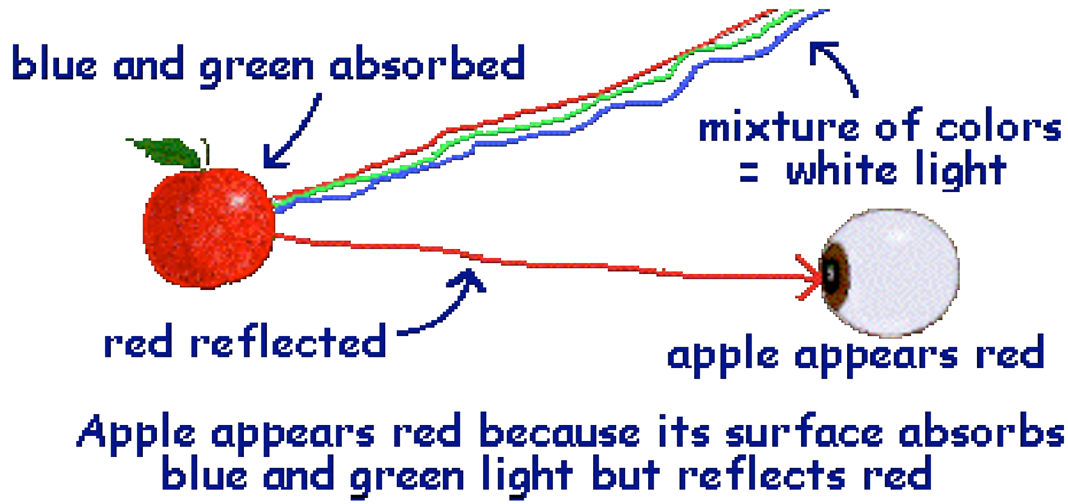
2 Explanatory Mechanisms:

A) **Opponent-processes**

B) **Color vision involves** ***spatial vision*.**

Recall Newton's (1672) analysis of object colors:

"The Rays to speak properly are not coloured. In them there is nothing else but a certain Power and Disposition to stir up a Sensation of this or that Colour. ... So Colours in the object are nothing but a Disposition to reflect this or that sort of Rays more copiously than the rest (1672)."



A more complete description of the reflectance properties of an object, however, involves the ***bi-directional reflectance distribution function*** **(BRDF)**. The BRDF describes the reflectance of lights in various directions as well as the wavelengths reflected in those directions. This is illustrated on the next slide.

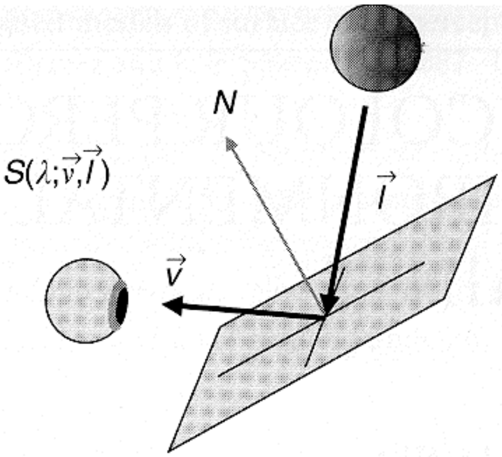


Figure 9.1 The bi-directional reflectance density function. The vector N is the unit normal to a specific point on a surface. The vector $\vec{l}$ is a unit vector from the same point on the surface in the direction of the light source and the vector $\vec{v}$ is a unit vector from the same point in the direction of the viewer. The bi-directional reflectance density function specifies the proportion of light of wavelength λ arriving along $\vec{l}$ that is re-emitted in the direction $\vec{v}$.

This diagram illustrates the definition of the BRDF. The BRDF describes the proportion of light reflected from a given surface in the hemisphere of possible viewing directions as a function of the hemisphere of possible illumination directions, and as a function of the spectrum of illumination. The BRDF is conceptually simple, but the large number of its degrees of freedom makes it very tedious to measure empirically, and difficult to use in computer graphics for synthesizing surface colors. (This figure is taken from L.T. Maloney (2003). Surface colour perception and environmental constraints. In R. Mausfeld & D. Heyer (Eds.), *Colour perception*, (pp. 279-300). New York: Oxford University Press.)

Different material substances have different BRDFs. ***Specular*** surfaces reflect light in a narrow direction, like a mirror—where the angle of reflectance equals the angle of incidence. Most surfaces are more ***diffuse*** reflectors, scattering light in a range of directions (usually greatest in the specular direction). The degree of scattering depends heavily on the microscopic roughness of the surface texture (at the scale of 100s of nanometers, near the wavelength of light). Smooth surfaces are shiny or transparent; rough surfaces are matte or opaque. Thus, surface microstructure affects macroscopic image structure.

Photographic illustrations of surface colors

The following photographs illustrate natural colors of environmental objects. Several important characteristics may be noticed:

(1) Color variations are accompanied by texture variations. Microscopic surface texture (at invisible scales) affects macroscopic, visible image structure—due to the way light is reflected and scattered by the surface.

(2) Solid objects are usually shaded, as the orientation of the surface varies relative to the direction of illumination and the orientation of the image. These images also contain shadows, that occur when one surface is between the illumination and another surface. Perceived object colors, however, usually are not changed by such shading and shadows.

(3) Many natural surface colors — e.g., metallic colors — cannot be produced simply by adding red, green, and blue light. Additive color mixture cannot account for the perceived surface colors of many natural objects.

(4) Currently available science and technology are insufficient for synthesizing most natural surface colors by computer graphics. (To do this, one must know the BRDF for the given surface material, but these are seldom known.)

Painted images

Despite the insufficiency of scientific knowledge about how to synthesize natural object colors, the following series of paintings (photographic reproductions from reproductions in books) illustrate that this achievement was mastered by painters in the 17th century.

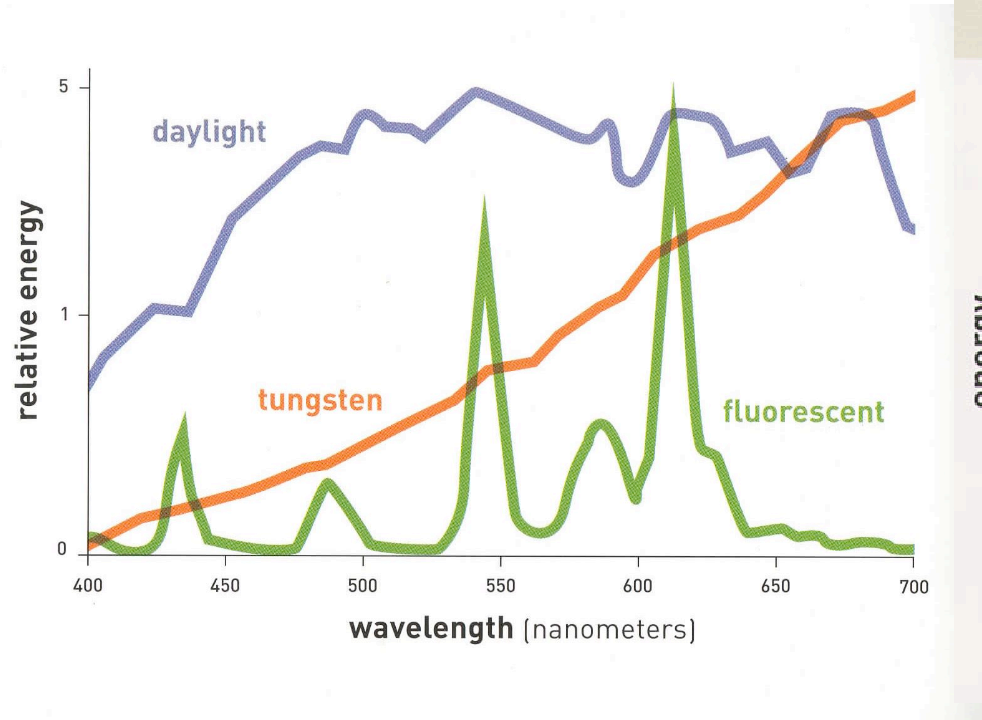
Edwin Land's experiments (c. 1960)

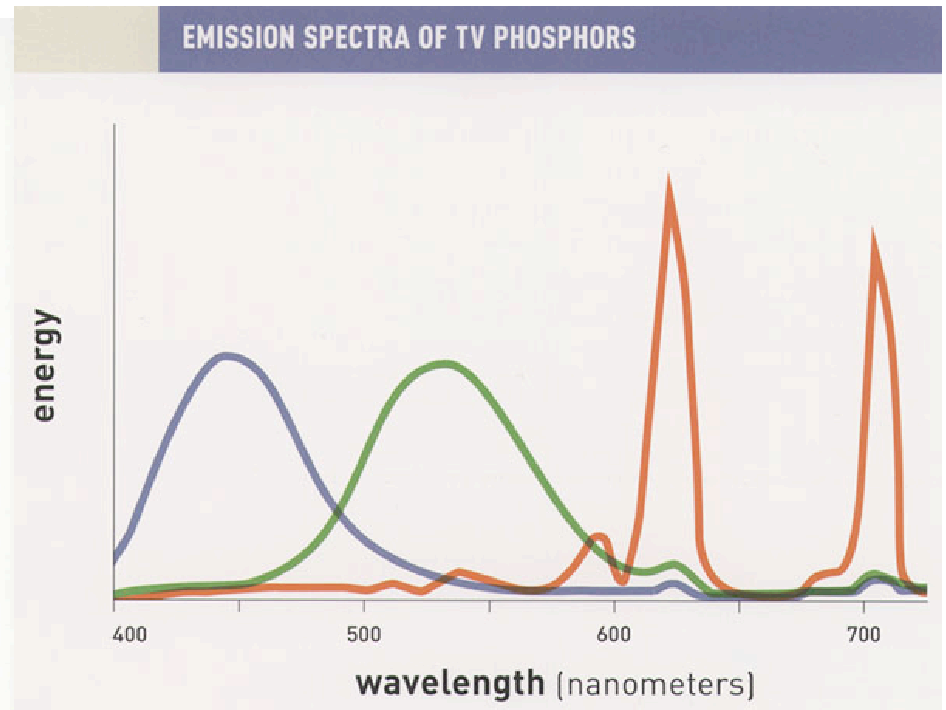
☛ *Demonstration #1:* Compelling colors from two images made with black & white film — one through a red filter, the other through no filter.

☛ *Demonstrations of color constancy with a color Mondrian viewed under various spectral illuminations.* (1) A given color patch may appear essentially the same under two different illuminations that yield very different patterns of responses in R, G, & B filters resembling retinal cones. (2) Two different patches seen as very different colors can yield the same pattern of intensities through the R, G, & B filters. In general, the perceived color of any given patch is <u>not</u> determined by the relative intensities of light received through 3 primary color filters from that patch alone. Color depends on the spatial surround.

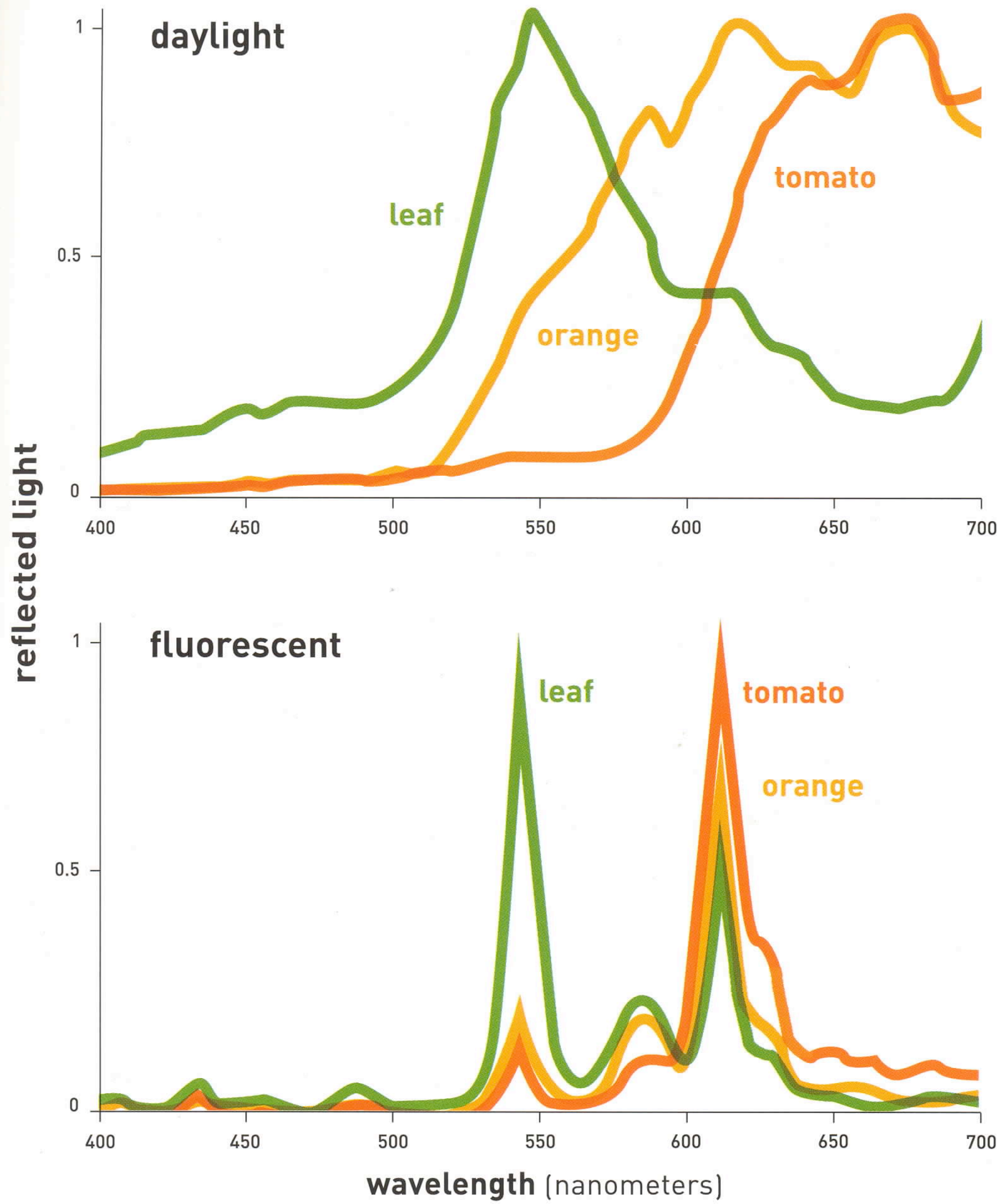
☛ <u>*A class demonstration*</u>.

Color Constancy: Stability of perceived colors under variations in illumination spectrum



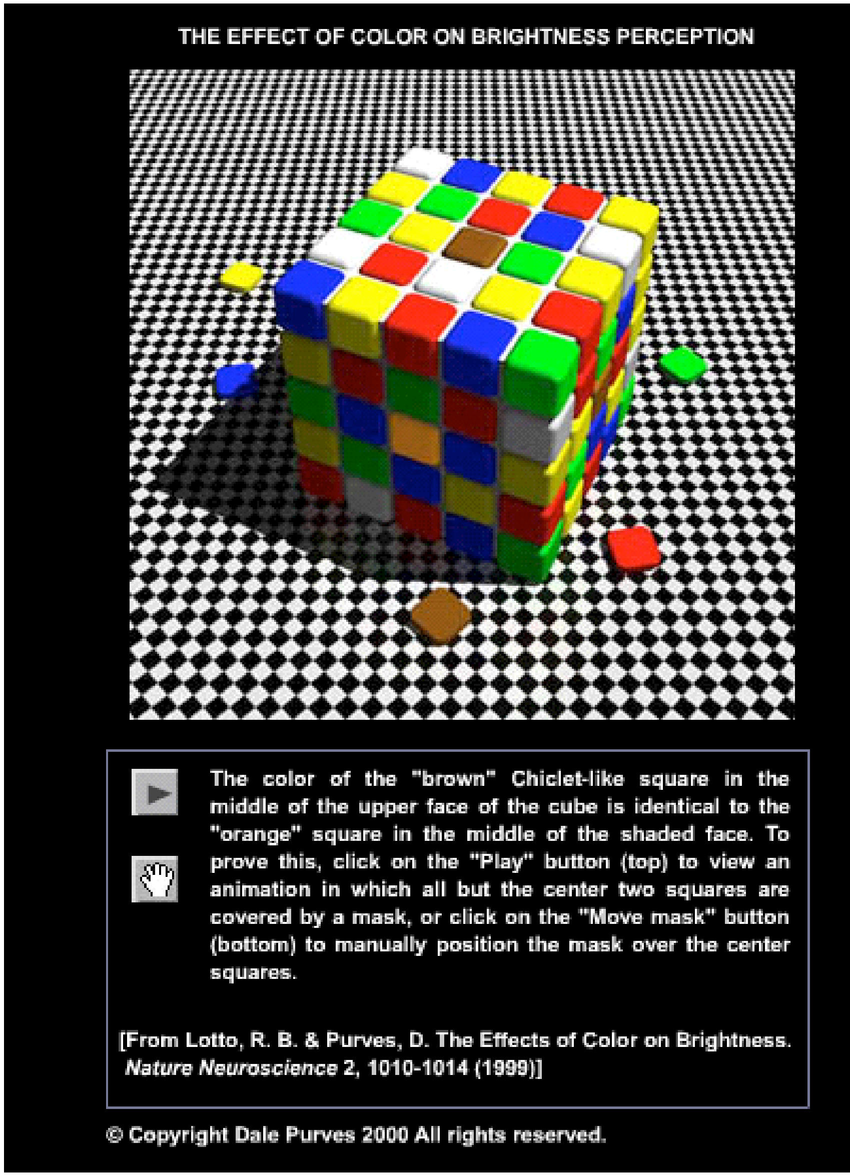


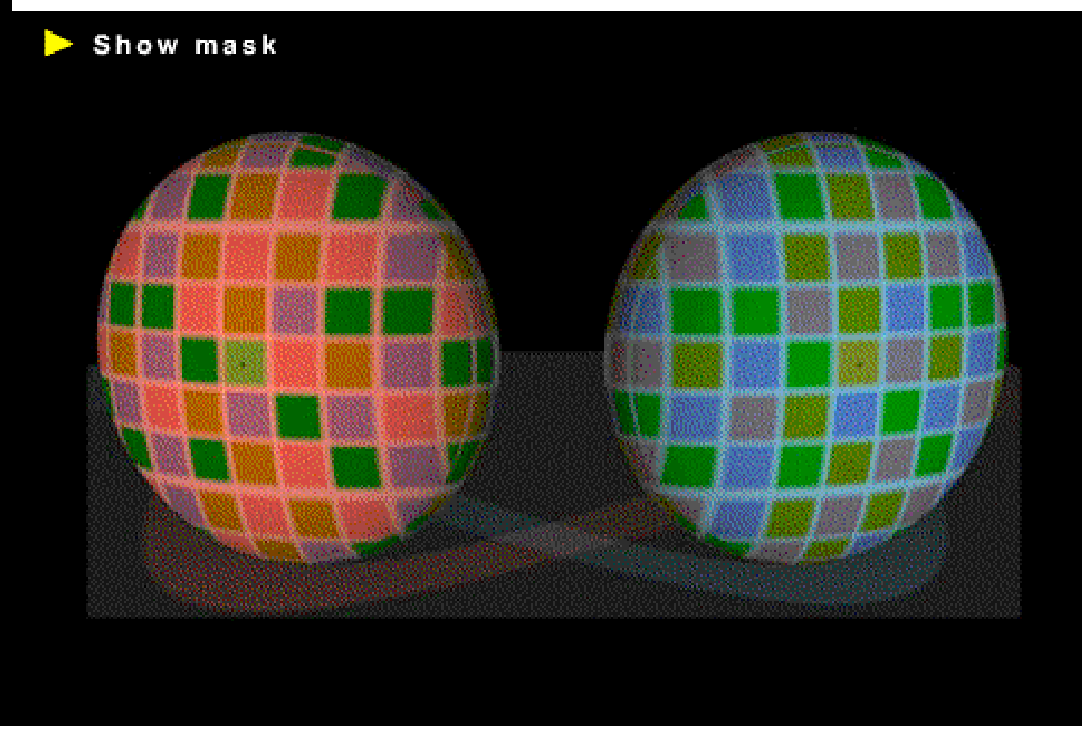
The illustrations on this and the following page are taken from Margaret Livingstone (2002), *Vision and Art: The Biology of Seeing*. New York: Harry Abrams.



daylight
leaf
orange
tomato
fluorescent
leaf
tomato
orange
reflected light
wavelength (nanometers)
1
0.5
0
400
450
500
550
600
650
700

These two illustrations (by Dale Purves) demonstrate that the perceived color of a given object depends on the surrounding colors and illumination. These “illusions” are the reverse side of color constancy; both show that perceived colors depend on the surrounding space and illumination.



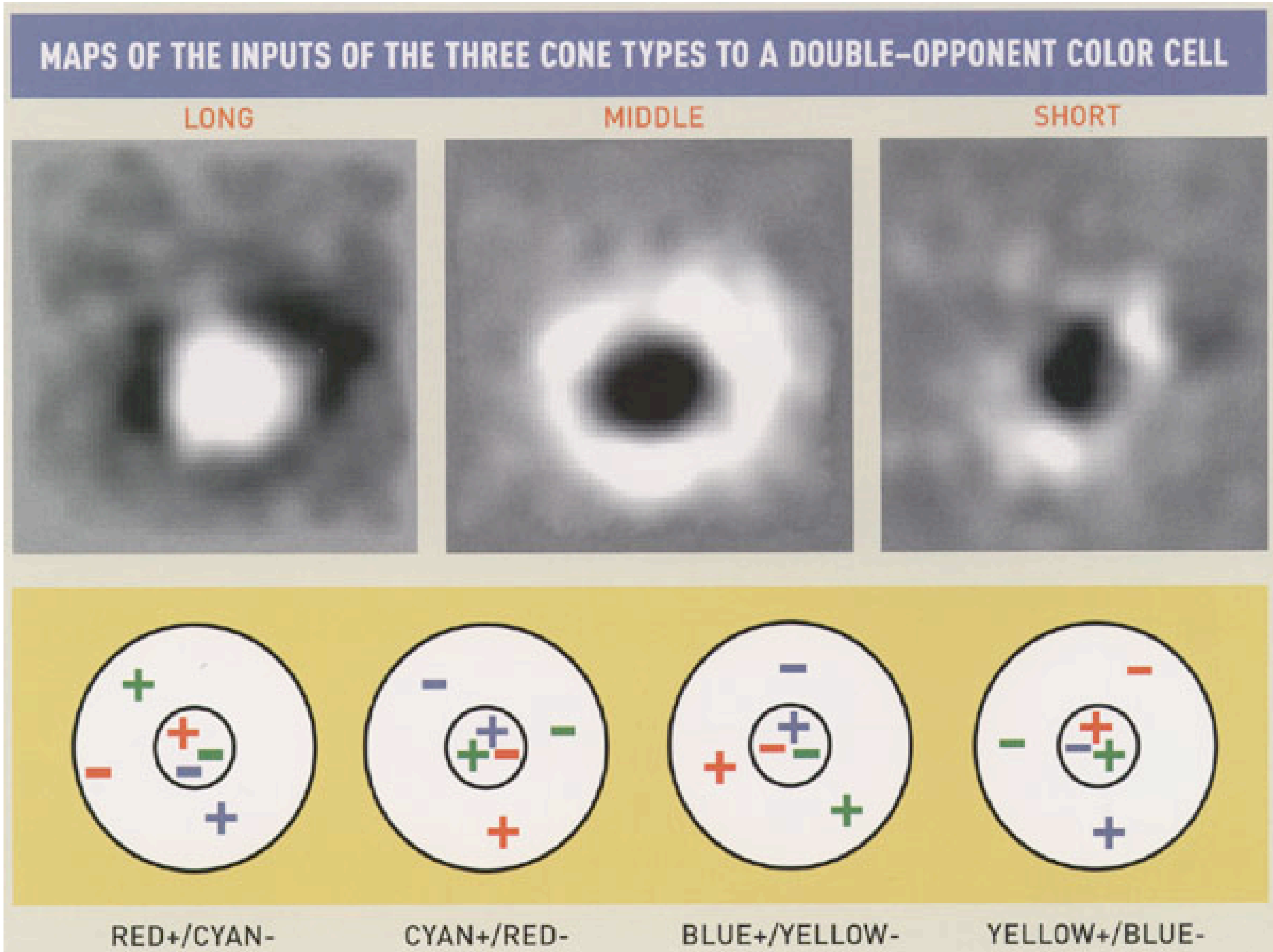


Edwin Land's experiments (c. 1960)

- ☛ *Demonstration #1:* Good colors from two images made with black & white film — one through a red filter, the other through no filter.

- ☛ *Demonstrations of color constancy with a color Mondrian viewed under various spectral illuminations.* (1) A given color patch may appear essentially the same under two different illuminations that yield very different patterns of responses in R, G, & B filters resembling retinal cones. (2) Two different patches seen as very different colors can yield the same pattern of intensities through the R, G, & B filters. In general, the perceived color of any given patch is not determined by the relative intensities of light received through 3 primary color filters from that patch alone. Color depends on the spatial surround.

- ☛ *A class demonstration.*

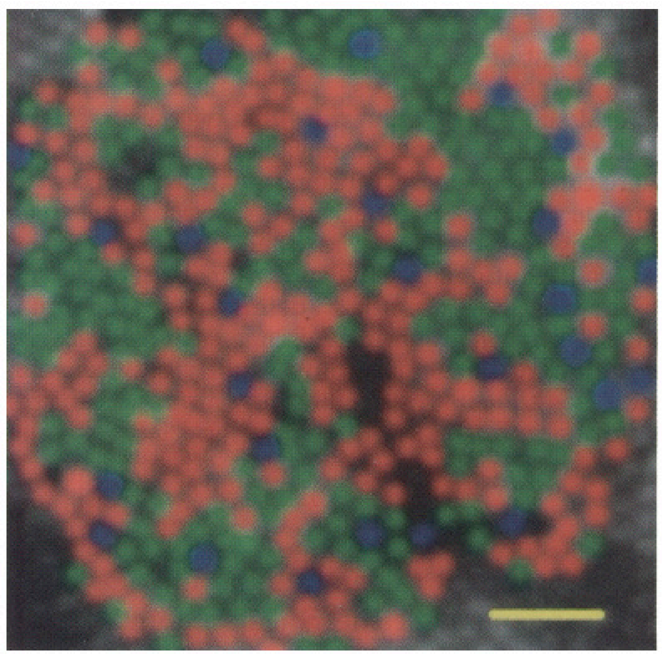


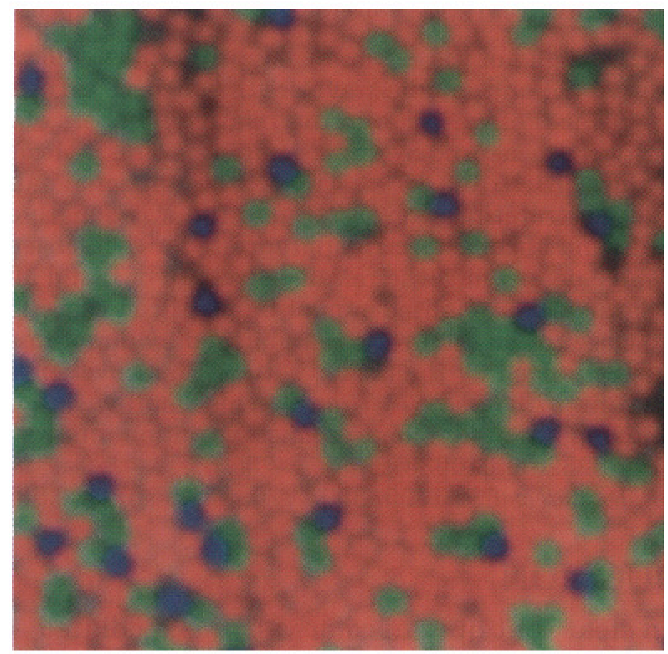
This illustration of "double-opponent" cells, from M. Livingstone (2002), depicts the receptive field organization of cells (in cortical area V4) jointly sensitive to both spectral and spatial variations. Some scientists believe that this mechanism is the basis for color constancy and related phenomena.

Recent findings about the visual effects of individual differences in the L/M cone ratio (Brainard et al., JOSA A, 2000, pp. 607-614.

Brainard et al used adaptive optics (developed in part by David Williams, one of the several coauthors) to image the retinal cones of two individuals. These cones could be classified as L-, M-, & S-sensitive by comparing photographs before and after selective bleaching. Photographs are below. The L/M cone ratios in these two retinas were found to be 1.15 and 3.79. The relative output strengths of these two cone classes was verified by flicker-ERG methods, obtaining similar estimates of the L/M ratios. The important question was how this difference in the L/M cone ratios affected color vision. To find out, the observers were asked to make forced-choice red/green judgments for 100 trials in which 5 different wavelengths (previously determined to be near an apparent yellow) were each presented 20 times in random order. The unique yellow was determined from the psychometric function as the wavelength chosen as green (vs. red) 50% of the time. The surprising result was that there was very little difference in the wavelength of unique yellow for these two persons — 577 and 575 nm! (The values predicted from their L/M ratios would have been ~ 600 and 520 nm.)

The findings of Brainard et al. indicate that the relative numerosity of L and M cones has little impact on perceived color. Interestingly, the following article in the journal, by Otake and Cicerone, concludes that the relative number of L and M cones probably does regulate individual variations in red-green color appearance (Otake & Cicerone, 2000, pp. 615-627). Brainard et al's methods seem more convincing, however.





Recap:

- *The impressive efficiency and robust performance of color vision is based on the "opponent process" mechanism.*
- *The visual system is remarkably effective in separating information about the reflectance characteristics of objects from the characteristics of (a) the measuring devices and (b) the ambient illumination. This is illustrated by the apparent robustness of perceived colors over variations in (a) the L/M cone ratio, (b) Land's demonstrations, and (c) color constancy.*
- *The "double-opponent" receptive fields of certain cortical cells exhibit interdependent sensitivities to variations in both color and space.*
- *Generally speaking, color vision is way cool.*