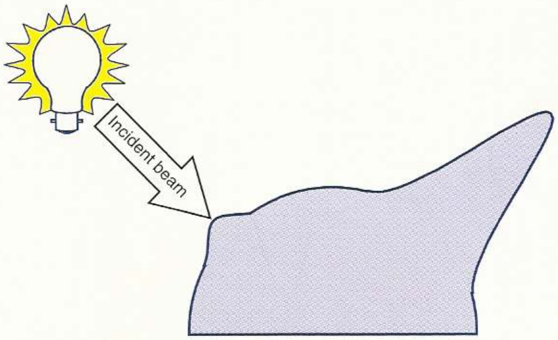
- **Haze (in transmisssion):** (1) The scattering of light by a specimen responsible for the apparent reduction in contrast of objects viewed through it. (2) The percent of transmitted light that is scattered so that its direction deviates more than a specified angle from the direction of the incident beam (ASTM E 284).



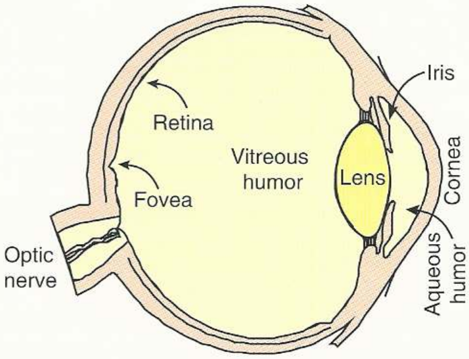
An *indicatrix* is a plot representing the amount of light scattered or reflected in that direction in comparison to the light scattered or reflected in the same direction by a perfect reflecting diffuser. The perfect reflecting diffuser results in an indicatrix that is a semicircle. Here we show an indicatrix of a semiglossy material.

Pearlescent colorants and metallic flakes, used in many applications such as automotive finishes and nail polish, affect both the goniophotometric and spectral properties of the incident light and are said to be *goniochromatic*. For fixed positions of the light source and the observer, the material's color changes as the specimen is rotated relative to the source and observer. In the automotive industry, the terms *face, near-specular,* and *flop colors* are used to describe the color of goniochromatic materials at three different rotations. If we view a goniochromatic specimen in a light booth, its face color corresponds to the specimen held at an angle parallel to the floor of the booth. When the specimen is rotated toward the observer, its near-specular color is seen. When the specimen is rotated away from the observer (corresponding to specular reflection aimed toward the back of the light booth), its flop color appears. Thus to completely characterize these materials, spectral measurements are required at several combinations of illumination and detection geometries. By convention, the sample position is fixed. Instruments for these measurements are called *goniospectrophotometers* when they sample at many continuous angles and *multi-angle spectrophotometers* when they sample at only a few angles. Goniochromatic materials and their measurement are described in more detail in Chapter 3, Section D.

C. PERCEIVING COLOR

So far, we have limited our discussion about *color* to the physical stimulus, producing light which, when detected and interpreted through our visual system, results in the stimulus having a particular *color*. The conversion from light energy to color names such as red, green, and brown is exceedingly complex. It requires an understanding of optics, detectors, neural processing, and cognition. Every year, vision scientists fill in more pieces of the puzzle. The comprehensive textbooks of Wandell (1995), Kaiser (1996), Backhaus (1998), and Palmer (1999) are suggested for more in-depth study. Fortunately, it is not essential for our purposes in this book to know in detail how the visual system works; knowledge of a few basic principles will suffice.

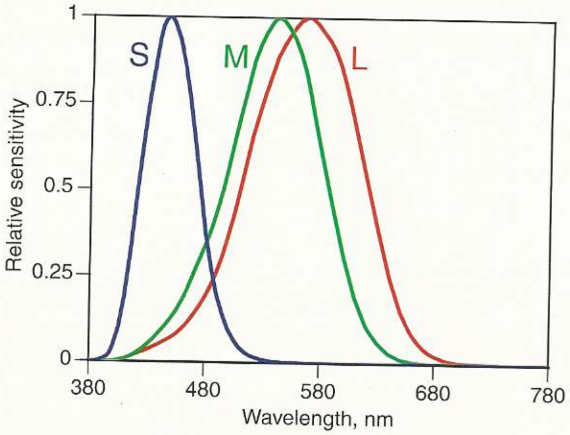
Light entering our eyes is imaged onto the back of the eyeball, the *retina*, where light *receptors* absorb a portion of the incident light and generate a signal eventually interpreted by the brain. In many respects, the image formation is similar to that in a camera (Falk 1986). The quality of the retinal image depends on the absorption, scattering, and focusing properties of the *cornea*, *lens*, and fluids filling the eyeball (*aqueous* and *vitreous humor*). These optical elements influence the spectral and spatial properties of the light receptors.



The cross section of the human eye.

There are two classes of receptors, rods and cones, named according to their shape. Rods detect very small amounts of light such as starlight. A single photon of light can produce a signal. Because there is only one pigment type, we only see objects as shades of gray. As the amount of light increases, the rods become desensitized and cease sending signals to the brain. During the day or in a well-lit room, the rod signals are inactive.

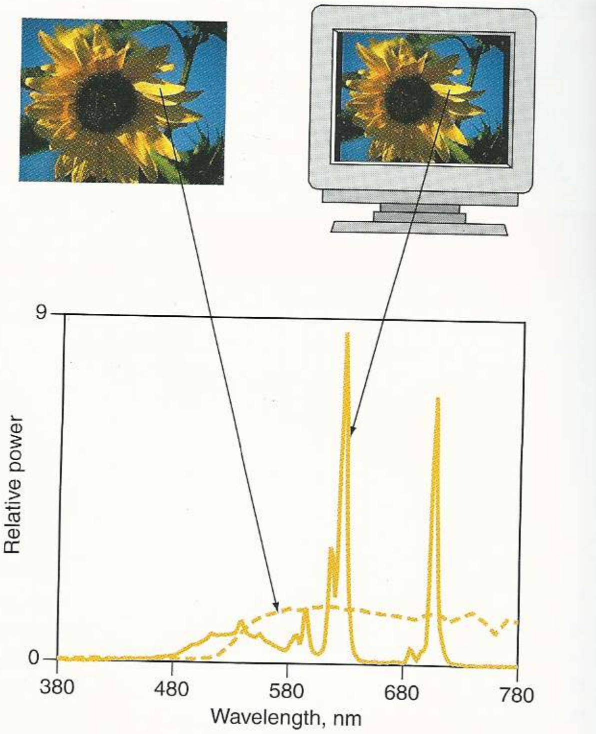
Cones, the second class of receptors, have much lower sensitivity to incident light. As the amount of light increases, the cones start sending neural signals. The cones are our color receptors. As the sun begins to rise in the morning, the gray world becomes colored. Our sensations of color are a result of having three types of cones responding differently to light of various wavelengths. Stimuli that cause different colors have different cone signals. The letters *L*, *M*, and *S* are used to represent the three cones with their peak sensitivities in the long, middle, and short wavelength regions, respectively. As shown in the figure on this page, their spectral sensitivities overlap quite a bit, particularly those of the L and M cones. This improves color discrimination. If the receptors did not have any overlap in their spectral sensitivities, we would only perceive three hues in the spectrum. Because of the uneven sampling of wavelengths, spectral differences are only rarely used to predict visual differences.



The relative spectral sensitivity of the L, M, and S cones (Stockman 1993). These spectral sensitivities are based on measurements in front of the eye rather than of isolated photoreceptors. Strictly speaking, these are called *cone fundamentals*. Schanda (1998) has summarized the relationships between cone fundamentals, their physiological bases, and how they relate to colorimetry.

When two stimuli, whether colored lights or illuminated materials, produce the same cone signals, the two stimuli match in color. Color matches can be calculated by knowing the cones' spectral sensitivities and the stimuli's spectra. The cones, as do any detectors of radiation, integrate (that is, sum up) the light at all wavelengths incident on them. Each such integration of all the incident wavelengths reduces the entire spectrum of incident light to three signals, one for each type of cone, resulting in what is called *trichromacy*. Trichromatic theory is usually associated with Young (1802) and Helmholtz (1866) although there is evidence that a number of scientists and technologists theorized the existence of trichromacy during the eighteenth century, notably Palmer in 1777 (Weale 1957).

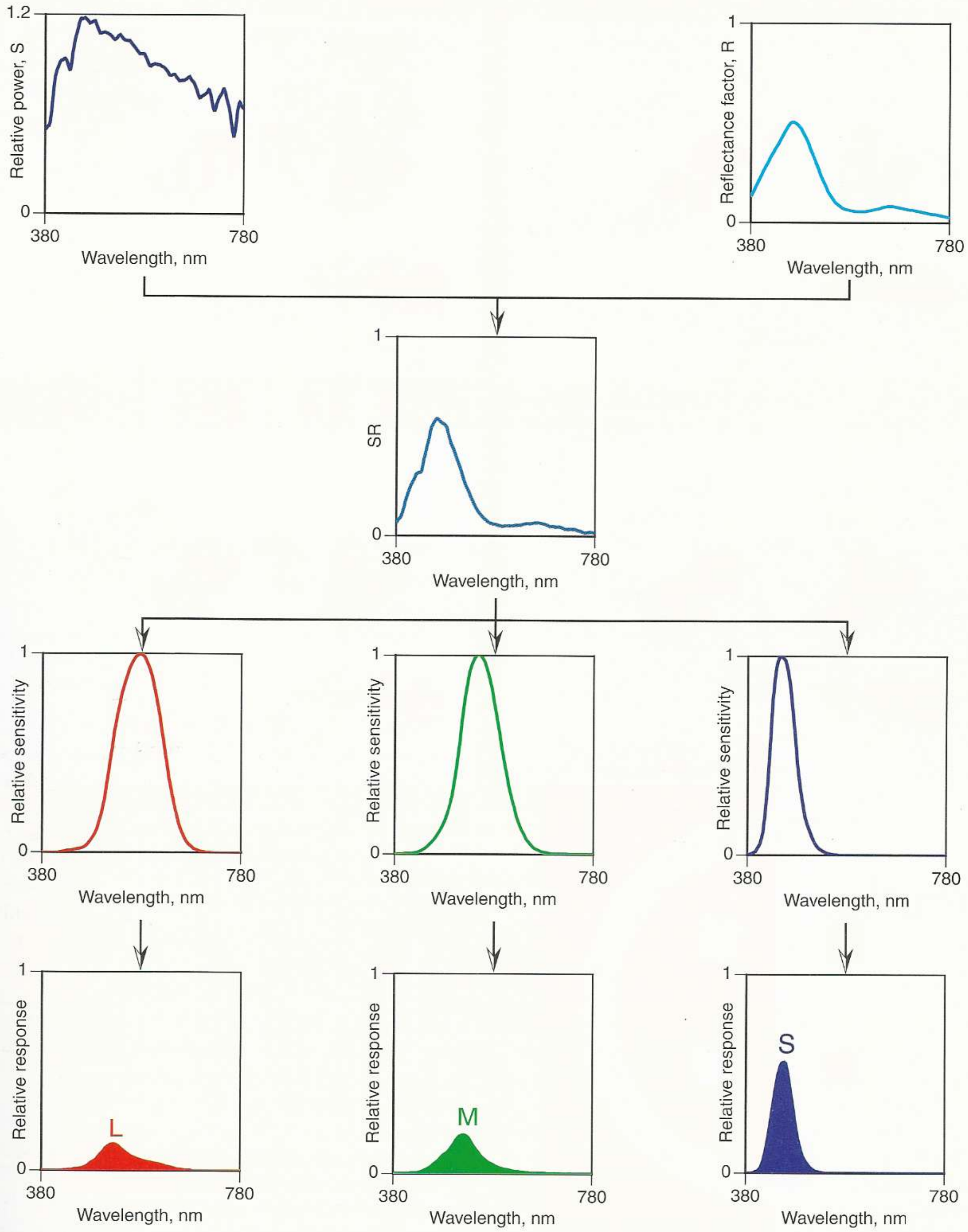
Trichromacy leads to perhaps the most important property of the visual system, *metamerism* (Grassmann 1853). Stimuli do not have to have the identical spectral properties in order to match in color. It is possible to match colors without matching physical properties. There are many examples of metamerism in our colored world. The three phosphors used in CRT displays produce a wide range of colors that match many objects. Because of metamerism, color reproduction is possible. Metamerism also occurs in ways that are detrimental to our colored world. Different materials often require different colorants. If the colorants are not carefully selected, metameric matches can be made, in which the materials match only for one set of standard lighting and viewing conditions. Imagine an automotive interior in which all of the colored parts match only in the showroom! We consider issues surrounding metamerism throughout this book.



The dashed line represents daylight reflecting from sunflower petals, while the solid line represents the light emitted by a color CRT display adjusted to match the color of the sunflower.

■ **Metamerism:** Phenomenon in which spectrally different stimuli match to a given observer. Metamerism (pronounced me-tam′-er-ism) comes from "metamer," a chemical term.

The rods and cones in the eye form a *retinal mosaic*. The detectors are closely packed as in a mosaic with the pattern varying in its arrangement throughout the retina. In the center of the eye or *fovea*, only cones are present, about 50,000. Foveal vision is used for distinguishing very fine detail, such as reading and seeing objects at a distance. A yellowish pigment, the macular pigment, is also present in the fovea. The macular pigment helps protect the foveal receptors from damage from the sun. Outside the fovea, the number of cones is greatly reduced and they are situated quite apart from one another. The remainder of the mosaic

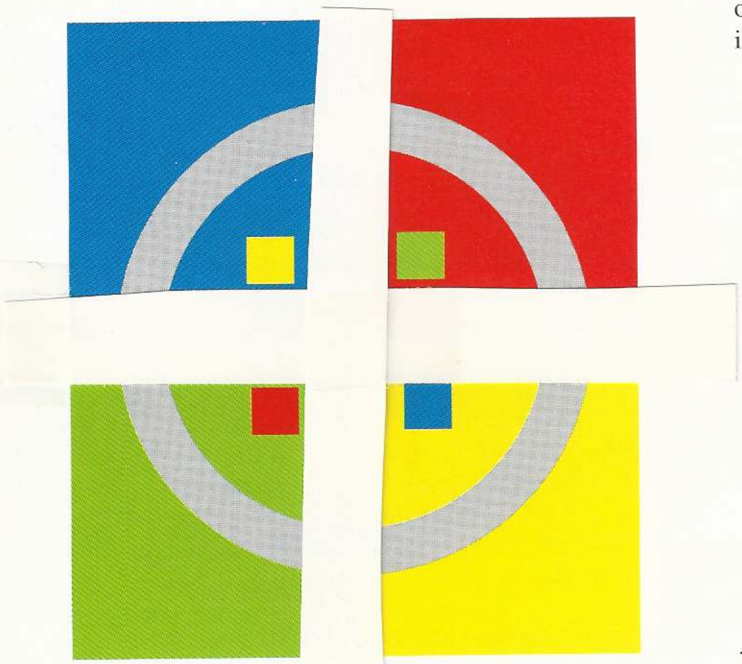


The integrated L, M, and S responses that result from the light entering the eye from an illuminated object. This can be calculated as the product of the spectral properties of the light source, the object, and the observer's sensitivities, followed by integration over wavelength, essentially, calculating the areas under the last row of curves. Integration is considered in detail on pages 56–59.

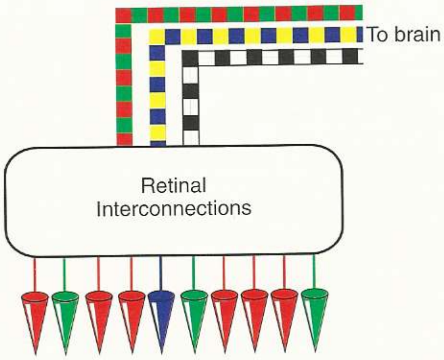
consists of rods. Each individual receptor does not have a separate connection to the brain; rather, receptors interconnect within the retina, forming *receptive fields* (Wiesel 1966). Thus *resolution*, the ability to resolve fine detail, depends ultimately on both the spatial mosaic of the receptors and how they interconnect.

There are many more L and M cones than S cones. The specific ratio is a current topic of debate but is about 6:3:1 for L:M:S (Curcio 1991, Hagstrom 1998). Because the optics of the eye have inherent limitations, short wavelength light is quite blurry by the time it reaches the retina. Therefore, having increased numbers of S cones is unnecessary.

In forming receptive fields, the individual cone signals can either add together or be subtracted from one another. Because the L, M, and S cones have different spectral sensitivities, different numbers, and different mosaics, the receptive fields have quite different properties. As a convenient simplification [see Lee (1996) for an in-depth review], we assume that there are three types of color receptive fields, called *opponent channels*. The black–white or *luminance* channel results from the addition of the L and M cones. It has the highest spatial resolution. The red–green channel is mainly a result of the M cones being subtracted from the L cones. Its spatial resolution is slightly lower than that of the luminance channel. The yellow–blue channel results from the addition of L and M and subtraction of S cone signals. It has very low spatial resolution. The concept of opponent channels was first postulated by Hering during the late 1800s (Hering 1878). He reasoned that trichromatic theory could not explain how red and green light combined to produce yellow light or that people with color-vision deficiencies confuse reds and greens or yellows and blues, exclusively.

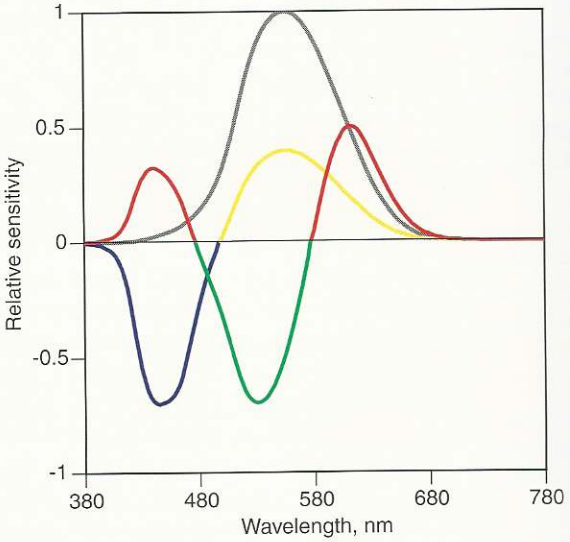


We can easily demonstrate rconnections that occur in the retina by surrounding a c different colors. Cut two thin pieces of paper and lay them across the gray circle, dividing it into quarters. Notice how the color of each quarter circle is different. Each small square has been produced with the identical amount of ink as its larger opposite square, yet the colors of the small and large squares appear different. (See also pages 24 and 25.)



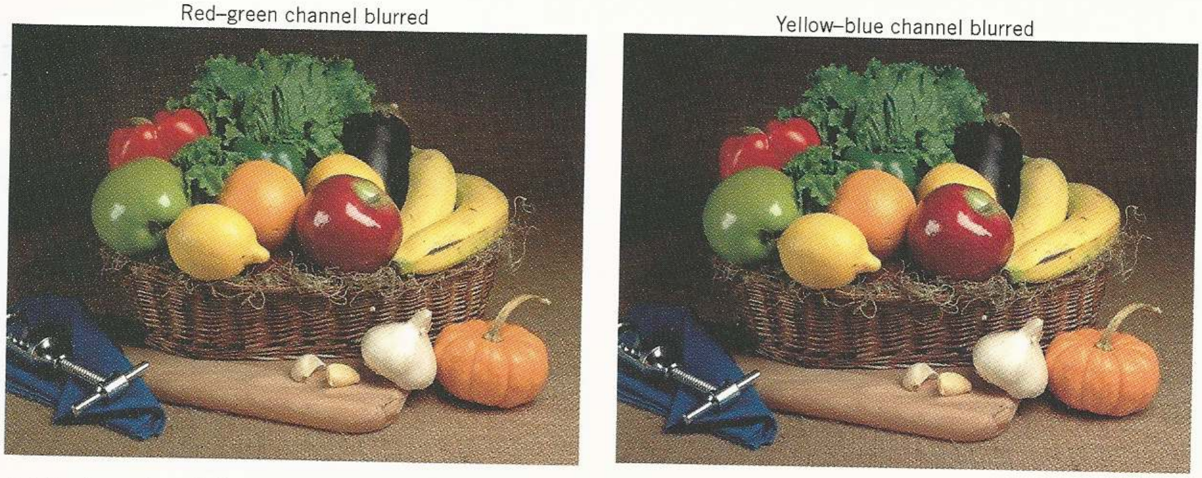
Cones interconnect in the retina, eventually leading to opponent-type signals.

Soon after Hering's ideas were first described, vision scientists argued whether the visual system was *either* trichromatic or opponent in nature. As we describe, both processes occur. They occur in stages as first suggested by von Kries (1882) and later by Schrödinger (1920) and Müller (1930). [Judd (1951) summarized these early stage theories.] However, stage theory could not be accepted until opponency was verified experimentally. This occurred during the 1950s (Jameson 1955, DeValois 1958).



The interaction of the three cone receptors forming opponent signals results in sensitivities with both positive and negative components (Hurvich 1981).

The differences in spatial resolution among the three opponent channels have been used to commercial advantage in broadcast television and digital color imaging. Television signals are encoded for transmission using signals



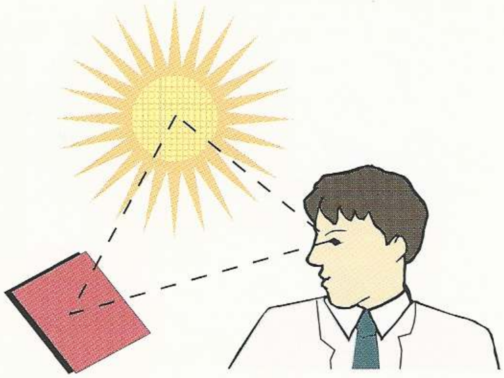
A color image is split into three separate channels: black–white, red–green, and yellow–blue. New images were made by blurring one of the three channels, then recombining the blurred channel and the two unaltered channels back into a color image. Although the amount of blurring was the same in each altered image, we only notice the reduced sharpness when the black–white channel is blurred. This demonstrates that we have reduced spatial resolution in our chromatic visual channels in comparison to our black–white channel. [After Wandell (1995). Digital image, courtesy of the Eastman Kodak Company.]

that are similar to those of the visual system's opponent channels. The spatial resolutions of the color signals are reduced before transmission, a great savings in signal content. In fact, without this reduction, it would not have been possible to develop color television signals during the 1950s that would also work on the much more popular (at that time) black and white television receivers (McIlwain 1956). Because of the limitations of the visual system's spatial resolution, we do not notice the loss of resolution when we watch television. This technique is also used when digital color images are compressed in a manner that results in a minimum of image quality degradation. Essentially, the color image is tranformed into opponent signals. The red–green and yellow–blue images are reduced in spatial resolution, then recombined with the full-resolution black–white image. This is known as *visually lossless compression* (Rabbani 1991). The method derived by the Joint Photographic Experts Group (JPEG) of the International Organization for Standardization (ISO) is the most common technique for the spatial subsampling (ISO/IEC DIS 10918-4). [See Wandell (1995) for a description of JPEG compression.]

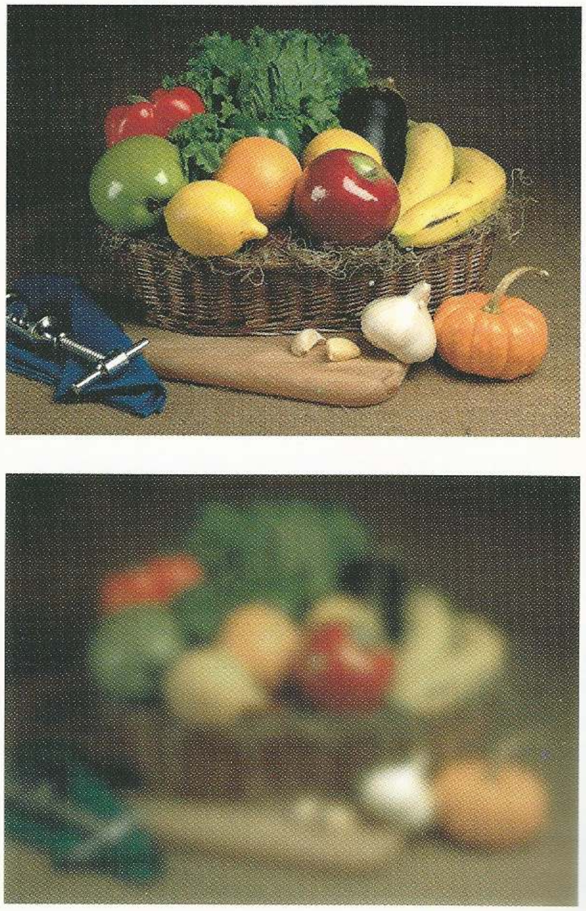
- **Visually lossless compression:** Reducing the amount of digital data defining an image in a manner that is not noticeable when viewed by an observer at a typical distance.

The opponent signals leave the retina via the optic nerve and eventually arrive at the back of the brain. The brain signals are interpreted through a cognitive process that results in *color.*

In summary, the visual system images the world onto the retina. The retina is composed of rods and cones, arranged in a mosaic. In very low light, the rods send signals to the brain resulting in monochrome perception. With an increase of light the cones start responding. There are three cone types, L, M and S, each with unique spectral and spatial properties. The cones combine forming opponent signals: black–white, red–green, and yellow–blue. The three opponent channels have different spatial resolution. By matching cone responses (or the equivalent opponent responses), it is possible for stimuli to match that do not have identical physical properties. These metameric stimuli are the basis for color reproduction and the matching of materials using very different colorants.



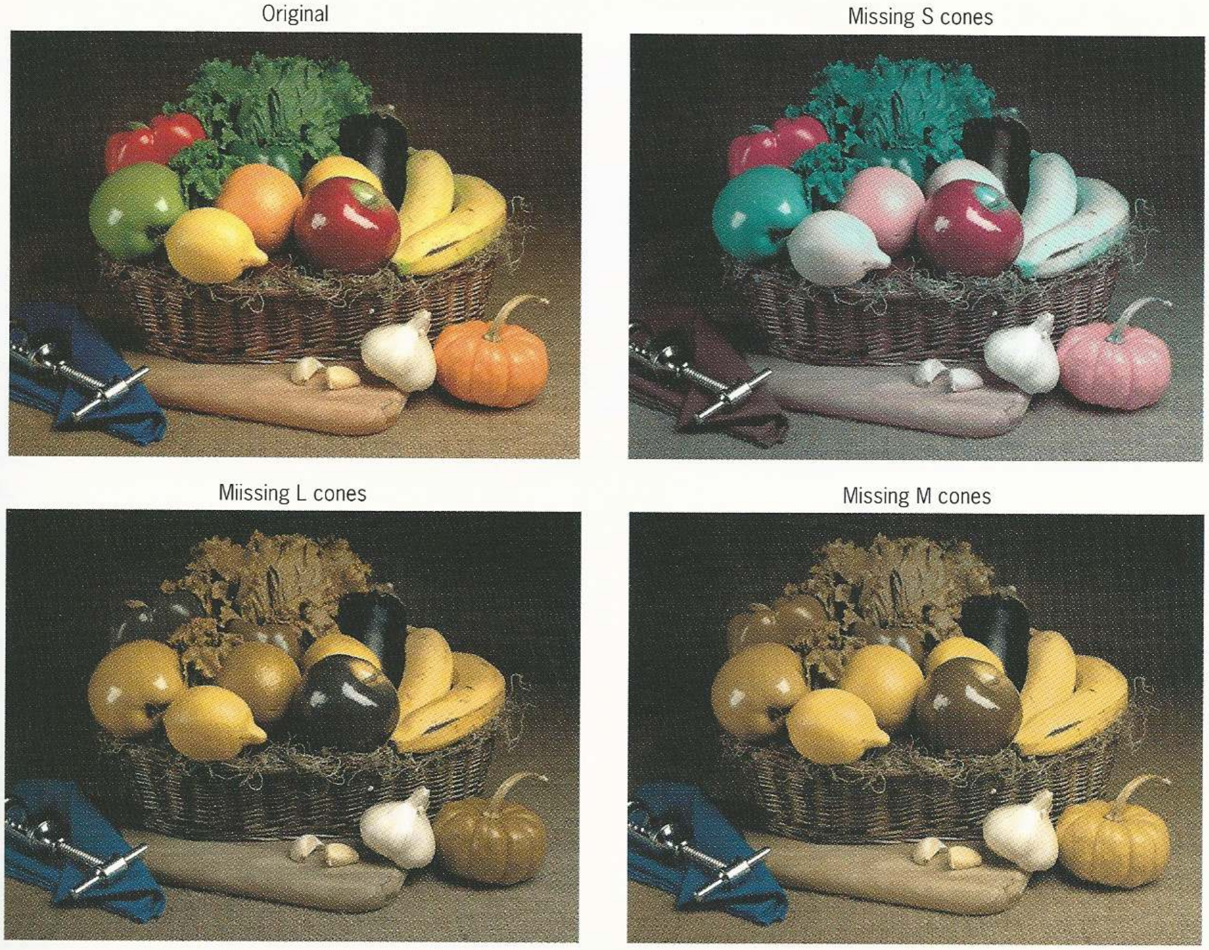
Unfortunately, there is a range of color vision in the human race. The chemical compounds that form color receptors vary among the population. The physical shapes of the receptors vary among the population and within the retina. The amount of macular pigment varies from person to person. Each person has different lens absorption and scattering properties. Thus, the color vision among observers with *normal color vision* varies significantly. The largest source of variability (Nayatani 1987) is caused by "yellowing" of the lens from exposure to ultraviolet radiation (Young 1991). The yellowing is due to both a reduction in the transmittance and an increase in scattering of short-wavelength light. When the scattering is extreme, the lens becomes nearly opaque and is called a *cataract*. The effects of this yellowing are gradual throughout our lifetimes. The French impressionist painter, Claude Monet, developed severe cataracts in the late stages of his life. Following the removal of his right eye's lens, he painted two canvases of his rose garden in Giverny, one using only the right eye and the other using only the left eye (Lanthony 1993, Werner 1998). The differences between the two paintings are striking: The right-eye painting is very bluish, while the left-eye painting is very reddish. The effects of cataract on perception can be simulated by looking at the world through yellow translucent glasses. Although our visual system will adjust to the yellow light to a large extent (known as chromatic adaptation, defined later in this chapter on page 25), the significant amount of blurring makes reading and other visual tasks difficult if not impossible.



A simulation of how this scene might appear to a person with cataracts. [See also Granville (1990).]

Devices used to quantify variability among color-normal observers are based on metameric matching and include the Glenn color rule, the Davidson and Hemmendinger color rule (Kaiser 1980, Díaz 1998), and the Macbeth matchpoint. Unfortunately, none of these devices is produced today. These color rules provide a tool for quantifying differences in color vision, particularly due to lens yellowing and cataracts (Granville 1990).

About 8% of the male and 0.5% of the female population have *color-defective vision* where either one or more receptor type is missing (known as *dichromats*) or one of the cones has spectral sensitivity that is shifted in wavelength (DeMarco 1992) (known as *anomalous trichromats*). Because of the specific underlying genetic defects, predominantly males are affected. The most common screening test was developed by Isihara (1962). Devices with greater



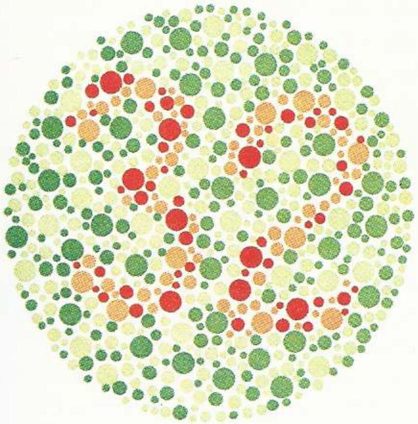
Original

Missing S cones

Miissing L cones

Missing M cones

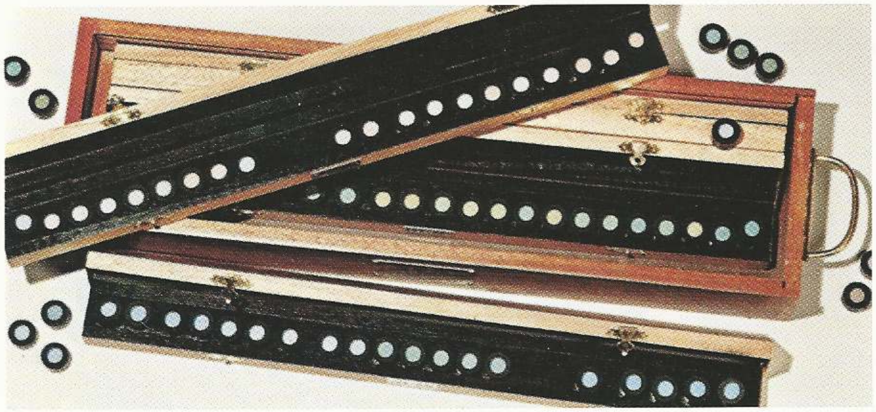
A simulation of what an observer missing either S, L, or M cones might see. Notice that the red apple and red pepper become very dark to an observer missing L cones. [After Burnham (1963). See Brettel (1997) for a more quantitative simulation.]



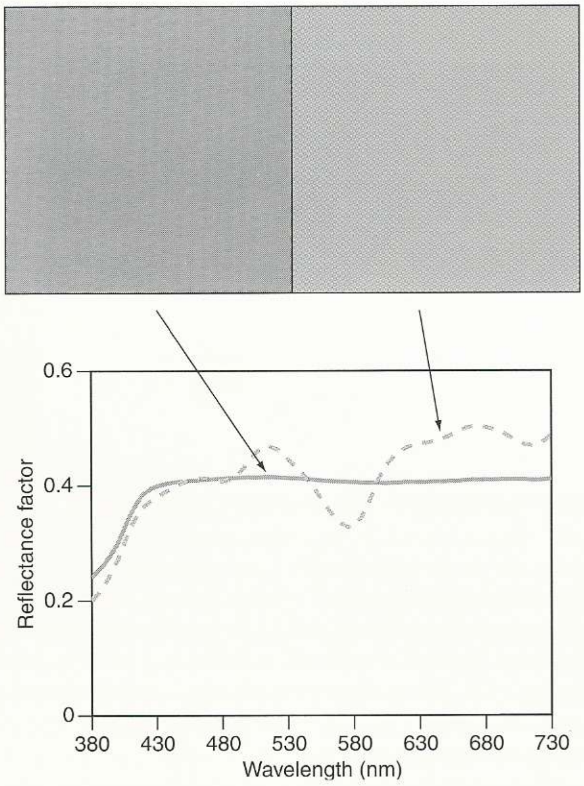
Pseudoisochromatic plates are random dots embedded with numbers. An observer missing either L or M cones will see this image only as a field of random dots. (Simulated Dvorine Pseudoisochromatic plate reproduced by permission. Dvorine Color Vision Test copyright© 1944, 1953, 1958 by Harcourt Brace Jovanovich, Inc. All rights reserved.)

precision include the Farnsworth–Munsell 100 hue test and the Nagel anomaloscope. Obviously, anyone involved in visual color assessments should have their color vision tested (National Academy of Science 1981, Birch 1993, ASTM E 1499).

The most important consequence of color vision variability, both color normal and color defective, is that metameric matches often mismatch when viewed by a different observer or in a different spatial location within the retina. The degree of mismatch can be severe. For this reason, much of color technology is based on using observers with average color vision properties in which light is assumed to be imaged on a particular location of the retina. These observers are known as *standard observers*. Furthermore, because of color vision variability, successful color technologists work very hard to produce color matches that are not metameric. We will have much more to say about both standard observers and producing nonmetameric matches.



Farnsworth–Munsell 100 hue test. Observers are instructed to order the colored caps in hue. Observers with color-vision deficiencies will make systematic errors, enabling diagnoses.



Each square is produced from different combinations of ink. The two halves should appear close in color under daylight illumination and different in color under incandescent illumination. Both halves form a metameric pair. Their spectral curves are shown below.

D. DESCRIBING COLOR

At this point we invite the reader to approach the subject of color with us from an entirely different point of view. Rather than describing the physics of materials and light, or the physiology of the eye, we want to provide a vocabulary for describing color as we see it. We seek nouns and adjectives that have universal meaning and whose meanings are intuitive. Color names such as orange and gray conjure reasonably consistent perceptions. In fact, eleven *basic color names* have been identified (Berlin 1999): white, gray, black, red, yellow, green, blue, orange, purple, pink, and brown (see review by Hardin 1998). However, two samples may both be "red," yet differ widely from one another. We need additional descriptions with greater precision within a basic color name. Finally, it is also useful to organize colors to form logical transitions between basic colors.

What basic color name would you visualize if a colored product is named "Quiet Refuge," or "Calm Air"? The answer is on page 34.

Organizing Colors—The Desert Island Experiment

One of the many possible approaches to describing color is the so-called "desert island" experiment discussed by Judd (1975) and others. Suppose a person with normal color vision and with no previous experience in dealing with colors was idling away her time on a desert island, surrounded by a large number of pebbles with similar texture having a wide variety of colors. Suppose, further, she wished to arrange these pebbles in some orderly way, according to their color. How can we describe color in terms of what she might do?

One can think of many different ways in which our lonely castaway might solve this problem; we shall describe only one. Let us assume that our experimenter, thinking about color in terms of the common names red, blue, green, and so forth, as most of us do, chooses first to separate all of this kind from those without hue—that is, those that are white, gray, or black. In other words we can say she separates the *chromatic* pebbles from the *achromatic* ones.

On examining the achromatic stones, our observer would find that they could be arranged in logical order in a series going from white through light gray to dark gray and finally black. This arrangement in terms of a single varying quality, *lightness*, provides a place for every achromatic pebble in the collection. Anothers common name for this