alone, but modify the neuron’s response to stimuli falling inside its receptive field. Wachtler et al. (2003) found that a cell that responded well to a bluish patch on a gray background responded less well when the patch was presented on a blue background. These neural effects shared certain features with perceptual contrast effects studied with the same stimuli. The similarity between neural and perceptual contrast effects supports the view that V1 "plays an important role in the neural processing that leads from the sensory signals to our percept" (Wachtler et al., 2003, p. 689).

COLOR CONSTANCY

What is the functional significance of color contrast and adaptation, and the cells that create these effects? The spectrum of wavelengths reaching the eye from an object depends jointly on the spectral reflectance properties of the object and the spectrum of the illuminating light (see Chapter 6). Relatively gross changes in the illuminating spectrum are not uncommon in everyday life. For instance, the spectrum of daylight varies markedly during the day from daybreak, through midday, to sunset. Artificial light has a greater preponderance of longer wavelengths than daylight, as shown in Figure 6.6. Despite such large changes in illumination, an object’s color (namely, our perception of its spectral reflectance) remains relatively stable. This effect is known as color constancy.

The spectral reflectance of an object is an inherent property of it that can be used for recognition and classification, so color constancy is clearly beneficial for object perception. How is it achieved? Foster and Nascimento (1994) computed cone excitations from a variety of reflective surfaces viewed under different illuminants. They found that the ratio of cone responses remains invariant under different illuminants. For example, if surface a excites red cones twice as much as surface b under a given illuminant, it will also excite red cones twice as much under other illuminants. Cone excitation ratios therefore provide a stable measure of surface reflectance properties, and offer a means for the visual system to discount the contribution of the illuminant.

Local contrast and adaptation phenomena can be viewed as evidence that cone excitation ratios are actually used to assign color. Indeed local contrast and adaptation have been identified as cues for color constancy. Other proposed constancy cues include (Hurlbert, 1999):

- Global contrast, based on cone responses averaged over the whole scene.
- Luminance maxima or highlights, which usually represent specular reflections from glossy surfaces. As mirror reflections of the light source, highlight color depends on its spectrum.
- Mutual reflections from one object to another in the scene, creating secondary light sources.
- The range of colors in the scene, which is indicative of the range of wavelengths in the illuminant.

A recent study of color constancy by Kraft and Brainard (1999) produced evidence that local contrast makes the largest contribution to color constancy, though other cues are also used. Kraft and Brainard showed observers a realistic scene containing various small objects and papers. Their task was to adjust the chromaticity of a test surface in the scene until it appeared neutral gray. Kraft and Brainard varied the illuminant and the cues

KEY TERM

Color constancy
The apparent hue of a reflective surface remains constant even when changes in the spectral power distribution of the illuminant alter the wavelengths reflected from it.
available. Baseline observations revealed that color constancy was by no means perfect (i.e., 100% resistant to illuminant changes), but attained a level of 83%. Kraft and Brainard found that when local contrast cues were removed, constancy fell to 53%. So, although local contrast is important, it is not the only cue used. Kraft and Brainard (1999) also found evidence for the use of global contrast and luminance maxima. With all these cues removed, constancy was still above zero, at 11%.

Although perceptual research has provided information on what visual cues are used to establish color constancy, there is as yet no universally agreed computational theory of color constancy.

COLOR DEFICIENCY

A frequently asked question about color vision is “How do I know that the color I see is the same as the color you see?” There is no way to answer this question definitively, of course, since colors are mental states. Most people use color names in the same way, and make the same judgments of the similarities and dissimilarities between colors. A fabric that I might describe as “crimson,” for example, would be given the same description by most other observers. However, about one in twelve people have very different color experiences from the rest of us. They may confuse crimsons with blues, and scarlets with greens. Such individuals are commonly called “color-blind,” though this label is a misnomer since most of them do see colors, but in a different way from normal observers. The more accurate clinical term is color deficient, because there is a reduced capacity to discriminate between colors. The existence of color deficiency has been known for centuries, but only in the last century was its cause traced to the properties of cone photopigments.

As discussed earlier, normal color vision is trichromatic in the sense that observers require three primaries to achieve a subjective match with any color. Color deficient observers behave differently in color matching experiments. They can be divided into three groups on the basis of their performance:

- **Anomalous trichromats** require three primaries to achieve metameric matches, but in proportions different from those required by normal observers.
- **Dichromats** require only two primaries to achieve metameric matches.
- **Monochromats** require only one primary.

Normal trichromacy can be related to the presence of three distinct classes of cone in the retina. Not surprisingly, color deficiency is linked to abnormal properties in the cones.

ANOMALOUS TRICHROMACY

The eye of the anomalous trichromat possesses three cone classes, but the spectral sensitivity of the cones is shifted relative to normal trichromats. The two major forms of anomalous trichromacy are protanomaly and deuteranomaly:

- In **protanomaly** the peak response of the long (red) wavelength cone class is shifted to shorter wavelengths, so that it is closer than normal to the peak of the medium (green) wavelength cone class. As a result, protanomalous observers are more sensitive to green wavelengths than normal observers.

KEY TERMS

**Color deficiency**
A reduced capacity to discriminate between colors, caused by an abnormality in cone photopigments.

**Anomalous trichromacy**
A form of color deficiency in which the individual possesses three different cone classes, but their spectral sensitivity is shifted relative to normal trichromats.

**Dichromats**
require only two primaries to achieve metameric matches.

**Monochromats**
require only one primary.

Both protanomalous and deuteranomalous color discrimination, both short and medium and long wave.