Chapter 1
The Nature of Color

1.1 Introduction

Electromagnetic waves can have many different wavelengths and frequencies in a range known as the electromagnetic spectrum, as illustrated in Fig. 1.1. Light is a narrow range of electromagnetic waves that the eye can detect. Different wavelengths of light produce different perceptions of color. The longest wavelengths produce the perception of red, while the shortest ones produce the perception of violet. The spectrum in the visible, ultraviolet (UV), and infrared (IR) regions is classified in Table 1.1.

Humans have been quite interested in color for many centuries. However, the scientific beginning of color studies goes back only to Newton when he performed his classic experiment with a prism, as shown in Fig. 1.2, and as detailed in Section 1.2.

The sensation of color is produced by the physical stimulation of the light detectors—known as *cones*—in the human retina. The color spectrum produced by an ideal prism or a diffraction grating is formed by a display of all of the spectrally pure or monochromatic colors. Each color has a different wavelength. The wavelength values corresponding to each color in the spectrum produced by a prism are quite nonlinear. The diffraction grating produces a more linear spectrum. For illustration purposes we will represent the spectrum with a linear chromatic dispersion, as illustrated in Fig. 1.3. Different spectrally pure colors are said to

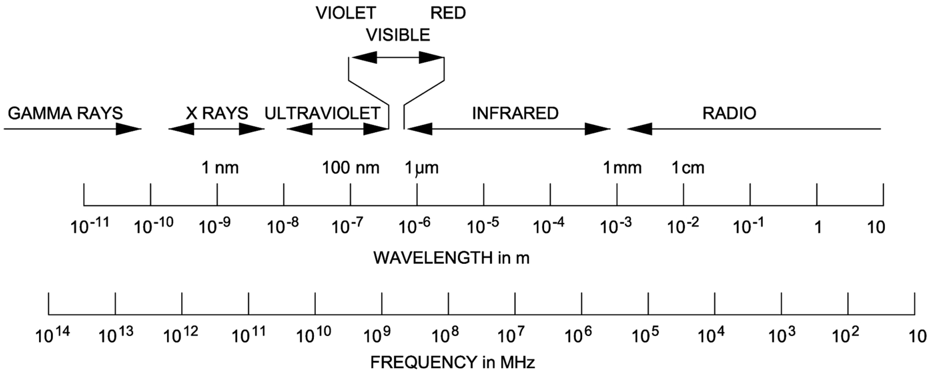

Figure 1.1 Electromagnetic spectrum.

Table 1.1 Ultraviolet, visible, and infrared regions of the electromagnetic spectrum.

Spectral region	Wavelength range (nm)	Subregion
Ultraviolet	100–280	UV-C
	280–315	UV-B
	315–380	UV-A
Visible	380–430	Violet
	430–500	Blue
	500–520	Cyan
	520–565	Green
	565–580	Yellow
	580–625	Orange
	625–740	Red
Infrared	740–1400	Near IR
	1,400–10,000	Far IR

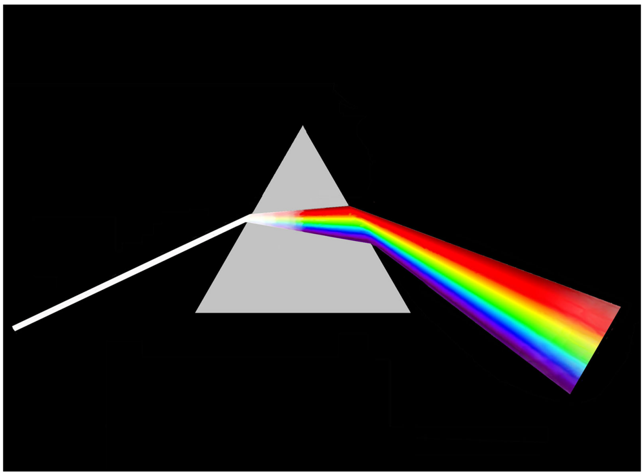

Figure 1.2 Newton's prism experiment.

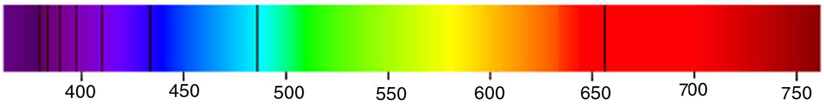

Figure 1.3 Color visible spectrum with hydrogen spectral lines as a reference.

have different hues. A spectrally pure or monochromatic color can be produced by a single wavelength. For example, an orange color is associated with a wavelength of 600.0 nm. However, the same color can be produced with a combination of two light beams: one being red with a wavelength of 700.0 nm, and another being yellow with a wavelength of 580.0 nm, and with no orange component with a wavelength of 600.0 nm. In conclusion, when we refer in this book to a spectrally pure light beam it does not mean that it is formed by a single-wavelength beam, as

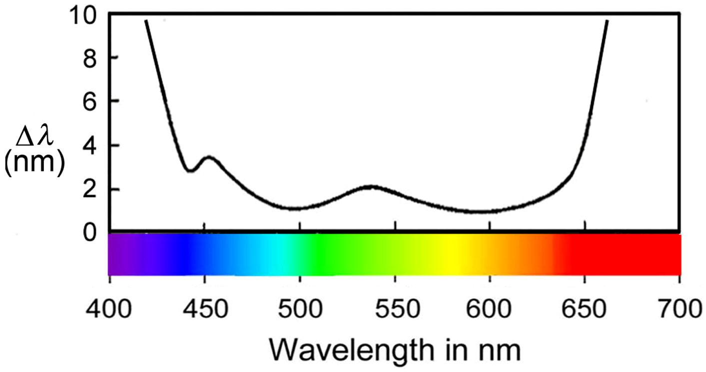

Figure 1.4 Color discrimination in a color spectrum.

in traditional physical or interferometry books (Born and Wolf, 1999). Instead, it means that it has the same color as the single-wavelength light beam matching its color. The two or more components used to produce a color cannot be identified by the eye, only with an instrument called a spectroscope. For this reason we say that the eye is a synthesizer device. In contrast, when the ear listens to an orchestra, the individual instruments producing the sound can be identified. Thus, we say that the ear is an analyzer. An interesting property of the spectrum is that the minimum wavelength separation between two close colors that can be identified as being different is not the same for different parts of the spectrum (Wright and Pitt, 1934). This is illustrated in Fig. 1.4. Colors arise due to the interaction of light with material bodies, for example, chromatic dispersion in glass or water, diffraction, etc. For a complete list of physical phenomena that may produce or modify colors, see Chapter 7 by Nassau in the book edited by Shevell (Shevell, 2003).

Color vision is not exclusive to human beings. Many animals also have this ability. The information contained in the light coming from the world around us is not only in the intensity, but also in its color. For this reason the study of color vision is quite important from an evolutionary point of view, as pointed out by Neitz et al. (2001). The human eye can distinguish about 200 different levels of gray, but the number of different possible combinations that the human eye can discriminate greatly increases with color vision, thereby expanding the amount of information that can be extracted from a scene.

Not all colors in nature are spectrally pure, since they can be mixed with white. In this manner, a mixture of red and white produces a pink color that goes from pure red (100% saturated) to white (0% saturated), depending on the relative amounts of red and white. Colors obtained by mixing a spectrally pure color with white are said to have the same *hue* but different *saturation*. The degree of saturation is called the *chroma*. The relative amounts of a mixture of white and a spectrally pure color determine the color saturation, or chroma.

Combinations of spectrally pure colors and white cannot produce all possible colors in nature. Let us consider two identical samples of a spectrally pure red color. If one of them is strongly illuminated and the other is almost in darkness, the two colors look quite different. In another example, if a pure red is mixed with some black paint, its appearance is different. In these two examples the difference between the two red samples is its lightness. Therefore, any color has to be specified by three parameters, i.e., hue, saturation (or chroma), and luminance, or any other three equivalent parameters, as will be described later in more detail.

1.2 Newton's Color Experiment

The history of the first color theories and experiments is quite interesting, as described in the review articles by MacAdam (1975), Neil and Steinle (2002), Mollon (2003), and Masters (2011). The first experiment in color, performed with a prism by Newton in 1671, demonstrated color dispersion. He used a triangular prism, as illustrated in Fig. 1.2, in a position so that a narrow beam of sunlight entering into the room passed through the prism. When this beam was projected onto a screen, a band of light with different colors appeared, forming what he called a spectrum (ghost). Newton said that the spectrum was formed by seven colors, i.e., red, orange, yellow, green, blue, indigo, and violet, probably in close analogy with the seven musical notes. This experiment immediately suggested the idea that white light is formed by the superposition of all colors. To prove this idea, Newton used another prism to recombine all colors from the spectrum into a white beam of light. Newton was very careful to state that the spectrum colors are not the only ones in nature. For example, new colors can be obtained by diluting them with the addition of white, thus changing their saturation. New colors can also be produced by increasing or reducing their intensity. In the case of paints, this is equivalent to mixing them with black paint or to increasing the level of illumination.

Newton also tried to recombine only certain parts of the spectrum by blocking out some colors produced by the first prism, by means of diaphragms. When he recombined two different bands of color, a third color appeared, frequently, but not always, matching one between these two. By combining the two ends of the spectrum (red and violet) in different proportions, he was able to obtain a new gamut of purple colors ranging from red to violet. Newton announced his investigations in color to the Royal Society of London in 1672.

The first color diagram was devised by Newton by drawing a circle listing all of the colors of the spectrum. Both spectrally pure colors and purple colors (produced by mixing in different proportions the colors at the ends of the spectrum) were drawn around the circle with white at the center, as shown in Fig. 1.5. Colors formed by a mixture of the pure spectral colors and white are between the center and the circumference. Complementary colors are on opposite points with respect to the center. If this circle is made on a piece of cardboard and placed on the axis of a rotating top, all colors mix to produce the impression of a colorless gray.

1.3 Theories and Experiments in Color Vision

After Newton's experiment, the next important contribution to the understanding of color came when Mariotte (1717) said that three colors are sufficient to produce

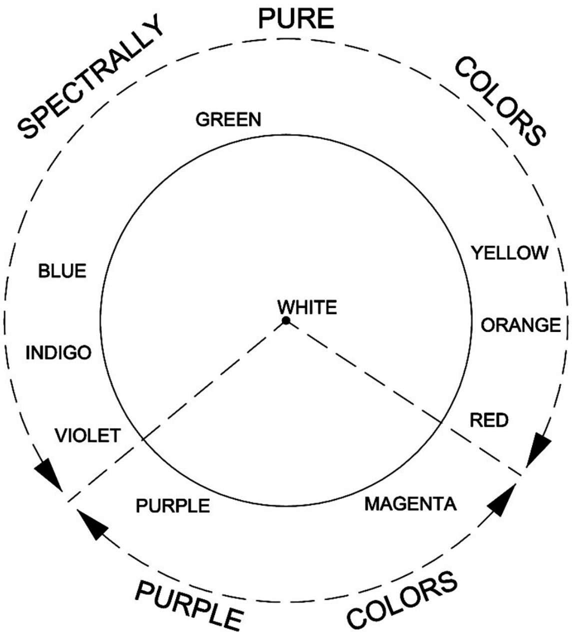

Figure 1.5 Newton's circle.

any color when using the proper combination of them. This concept was formally reintroduced by Palmer (1777) in a manuscript that was discovered in 1956, adding the concept of three different color receptors in the retina. In 1801, probably unaware of the previous work by Palmer, Young (1802) refined the trichromatic theory of color and postulated that all colors in nature could be matched with three different colors, which he called primary colors. He also postulated that the eye has three types of photoreceptors, one for each primary color. The problem with this theory is determining which colors are primary.

This so-called trichromatic theory of color was found satisfactory, but it did not explain many details. About 50 years later von Helmholtz (1852, 1866) revived and improved Young's ideas by adding more details based on experiments. For this reason, the trichromatic theory of light is now known as the Young–Helmholtz theory. Around this time, many other researchers were doing interesting optical color experiments. For example, Peirce (1877), who is considered the first experimental psychologist, made several color experiments that were described in a notebook labeled "Hue," and Rayleigh (1881) studied the matching of colors by many people.

Hering (1964) noticed that yellow and blue appear to be opposite colors. In other words, there is no bluish yellow or yellowish blue. In the same manner, red and green are opposite colors. Hering proposed a theory to explain this with four colors—red, yellow, green, and blue—as primaries. (Later, we will see that although this theory is not correct in detail, it has some interesting concepts that deserve consideration.) Hering assumed that the brain has a detector for yellow and blue light, followed by a classifier to determine the relative luminance of these two

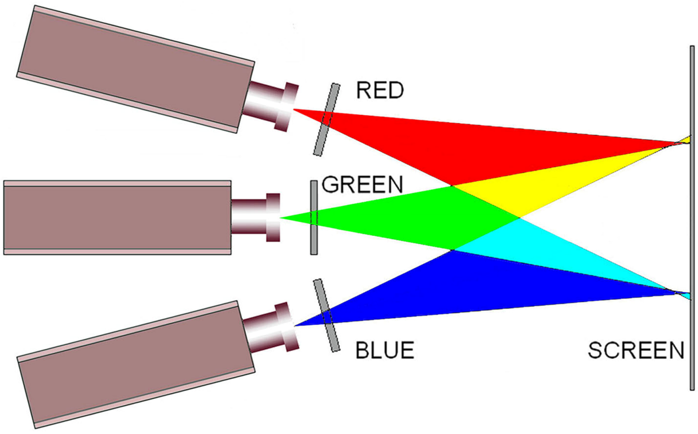

Figure 1.6 Maxwell's experiment.

colors. In the same manner, he assumed another detector for red and green light, followed by another brain classifier to determine the relative quantities of these two colors. Further, he assumed another classifier for white and black.

Almost simultaneously with the work of von Helmholtz (1861), Maxwell (1856, 1857, 1860, 1885) studied the perception of color and performed an experiment, as illustrated in Fig. 1.6, to produce a fully colored image, thus proving the Young–Helmholtz theory. He took three black and white photographs (positive transparencies) of the same scene (a colored ribbon), using three different colored filters in front of each of the three shots. Then, he projected the three pictures simultaneously with three projectors with each of the three colored filters in front of each projector. He assumed that the black and white photographic emulsion was equally sensitive to the three used colors. Unfortunately, his basic assumption was far from being true, since the photographic films used at the time were much more sensitive to the blue light. Evans (1961) describes that Maxwell obtained reasonably good results (with a color deficiency in the red and green) in spite of this because the three colored filters transmitted some light in the ultraviolet. In 1890, König (1903) assumed in a formal manner the previous hypothesis by his predecessors that there are three color detectors in the eye: one for red, one for green, and another for blue light. Frederick E. Ives (1888) repeated Maxwell's experiment using photographic emulsions that were sensitive over the whole luminous spectrum, and set up the main principles that led to modern color photography.

The *zone* color theories combine the opponent and trichromatic models. According to these theories, the trichromatic signals produced by the cones in the retina are sent to the brain, where they are converted into three opponent signals, two of them chromatic and one achromatic. These theories have now been discarded, but not completely, as we will describe in Section 5.7.

Ribe and Steinle (2002) point out that von Goethe (1988) contributed important research in color vision and published a book in 1810 entitled *Theory of Colors*.