2
Color Vision and Color Specification Systems

2.1 MECHANISM OF COLOR VISION

The mechanism of how colors are perceived has long been an object of interest, and numerous hypotheses have been proposed. Referring back to Figure 1.3, we know that the human eye can distinguish the various colors of the spectrum dispersed by a prism. Accordingly, one simple hypothesis assumes the presence of a different type of photoreceptor for each of the spectral colors. Because we can distinguish spectral colors differing from each other by only a few nanometers (nm), this hypothesis implies the existence of about 100 types of photoreceptor with different spectral responsivities. Thus it is somewhat unrealistic. Other polychromatic hypotheses propose the presence of six or seven types of photoreceptor, but the two most convincing hypotheses are the trichromatic theory originally proposed by Thomas Young and Hermann von Helmholtz, and the opponent-color theory originally proposed by Ewald Hering.

The *trichromatic theory* was proposed by Young (Figure 2.1) in 1802. The theory was expressed quantitatively and extended by

Colorimetry: Fundamentals and Applications N. Ohta and A. Robertson

Figure 2.1 Thomas Young (1773–1829)

Helmholtz (Figure 2.2) in 1894. It postulates that the retina comprises three types of photoreceptor (cones) which sense red, green, and blue colors respectively, and that all colors are characterized by the degree of response of these photoreceptors. For example, the sensation of yellow is generated by the simultaneous response of the red and green photoreceptors. The trichromatic theory is simple and readily understood because it assumes only three photoreceptors. Figure 2.3 shows the spectral responsivity of the three photoreceptors according to modern knowledge (Judd and Wyszecki 1975). Note that the peaks do not really correspond to red, green and blue spectral colors, so it is more accurate to describe the photoreceptors as long-, medium- and short-wavelength photoreceptors, respectively. Trichromatic theory is based on the experimental result that

Figure 2.2 Hermann von Helmholtz (1821–1894)

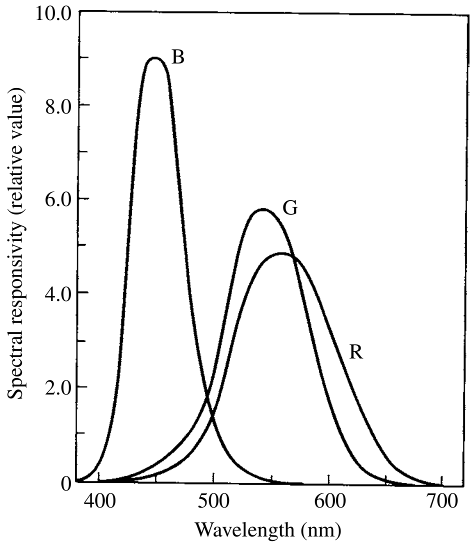

Figure 2.3 Spectral responsivities of red (R), green (G), and blue (B) photoreceptors in the trichromatic theory (Judd and Wyszecki 1975). Reproduced by permission of John Wiley & Sons, Ltd

almost all colors can be reproduced by properly mixing three lights, usually red, green and blue. Color TV sets, color photography, color printing, etc., are all based on the trichromatic theory, and their color reproduction can be excellent. Accordingly, the trichromatic theory is a realistic and convincing hypothesis.

On the other hand, Hering (Figure 2.4) proposed a hypothesis in 1878, which says that the retina comprises three types

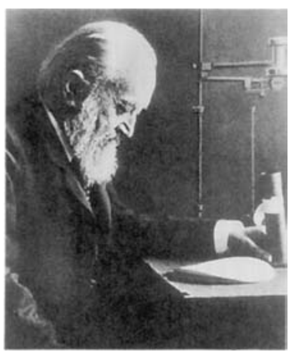

Figure 2.4 Ewald Hering (1834–1918)

of photoreceptor, which respond to red–green, yellow–blue and white–black opponencies respectively, and that all colors are characterized by the degree of response of these photoreceptors. For example, the first type of photoreceptor responds in a positive fashion to red and in a negative fashion to green. This theory is called the opponent-colors theory, and is based on empirical facts showing that there can be a yellowish red and a bluish red, but no greenish red, and that therefore green and red are opponent colors. Figure 2.5 shows the spectral responsivities of the assumed opponent-color photoreceptors. In the figure, positive and negative values have no particular significance, but for example, show that red and green are opponent colors (Judd and Wyszecki 1975). Because four colors, i.e., red, green, yellow, and blue are regarded as fundamental in the opponent-colors theory, the theory is also known as the four-color theory.

The trichromatic theory and the opponent-colors theory are each empirically based, and both can explain various color vision phenomena without facing any contradictions. Accordingly, it is difficult to decide which is the actual phenomenon that is occurring in the retina. However, the use of microscopic techniques has enabled the measurement of spectral absorption spectra for single cones in the retina. For example, in 1964 Brown and Wald reported the

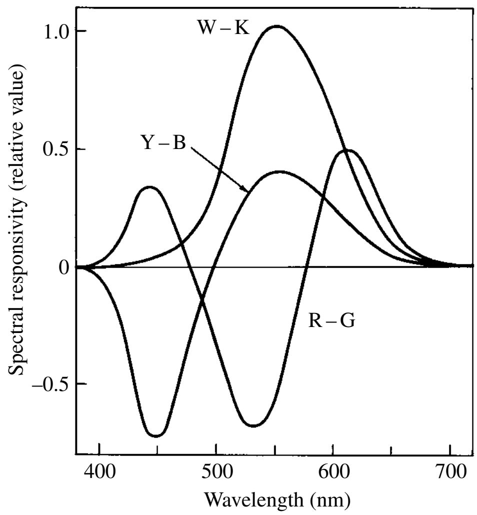

Figure 2.5 Spectral responsivities of red–green (R–G), yellow–blue (Y–B), and white–black (W–K) photoreceptors in the opponent-colors theory (Judd and Wyszecki 1975). Reproduced by permission of John Wiley & Sons, Ltd

[Image not available in this electronic edition.]

Figure 2.6 Spectral absorption in human cones (Brown and Wald 1964). Reprinted with permission from Visual pigments in single rods and cones of the human retina, *Science* **144**. Copyright (1964) AAAS

results shown in Figure 2.6 (Brown and Wald 1964). The results clearly indicate the presence of three types of cone having peaks at wavelengths of about 450, 525 and 555 nm respectively, as suggested by the trichromatic theory. Furthermore, thanks to progress in electrophysiology, a method of directly measuring the electrical response of cones to colored lights has been employed by placing a microelectrode about 0.1 μm in size in the retina. Figure 2.7 shows

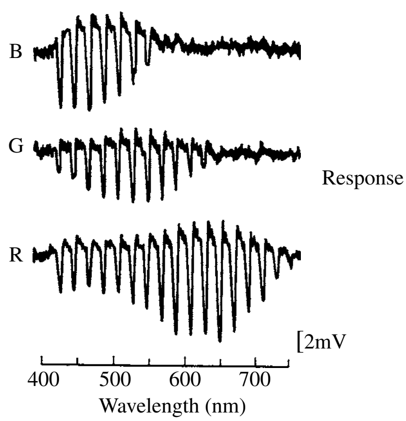

Figure 2.7 Trichromatic response of carp cones (Tomita 1967). Reprinted from *Vision Res.* **7**. T. Tomita, A. Kaneko, M. Murakami and E. L. Pautler, Spectral response curves of single cones in the carp, 519–531(1967), with permission from Elsevier

the measured results obtained by Tomita on carp in 1967, and it also clearly shows a trichromatic response similar to Figure 2.6 (Tomita *et al.* 1967).

It seems from these results that the trichromatic theory explains the mechanism of color vision. However, by inserting microelectrodes into the retina, Svaetichin (1953) had already found an opponent-type spectral response known as the S potential 1953. The S potential, shown in Figure 2.8, supports the opponent-colors theory and was initially believed to be the response of cones, but Tomita revealed by detailed measurements that it came from a region several tens of μm distant from the cones. From these results it has emerged that a trichromatic response is present in the cones and then the electric signals generated there undergo processing which obeys the opponent-colors theory in the horizontal cells, amacrine cells, etc., to be finally transmitted to the brain via ganglion cells.

The spectral absorption spectra of the rods functioning in scotopic vision was measured by Crescitelli and Dartnall (1953) to give the results shown in Figure 2.9. As expected, the absorption spectrum is very similar to $V'(\lambda)$, the luminous efficiency function for scotopic vision. In conclusion, it is now known that the retina comprises rods and three types of cone, and that they work cooperatively to realize vision which responds to a vast range of brightness and color from 0.0003 to 100 000 lx, an operating range of about 8 decades.

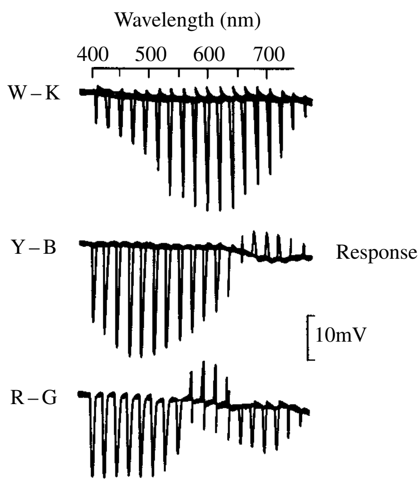

Figure 2.8 S potential in the carp retina (Tomita 1963). Reproduced by permission of Optical Society of America

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Figure 2.9 Absorption spectrum (∘) of rods and $V'(\lambda)$ in scotopic vision (Crescitelli and Dartnall 1953). Reprinted with permission from Nature, Human visual purple, Macmillan Magazines Limited

A model that explains the phenomena of color vision by combining the four types of photoreceptor is called a color vision model. Numerous models have been proposed. The most convincing of these are stage theories that are based on the results of psychological experimentation, of microscopic spectral measurement, and of electrophysiological measurement. Such models assume a trichromatic response at the cone level and an opponent-colors response in later stages. Figure 2.10 is the color vision model proposed by Vos and Walvaren (1971). In this model, the brightness response of the rods and the red (R), green (G), and blue (B) response of the cones are assumed for the first step. The response

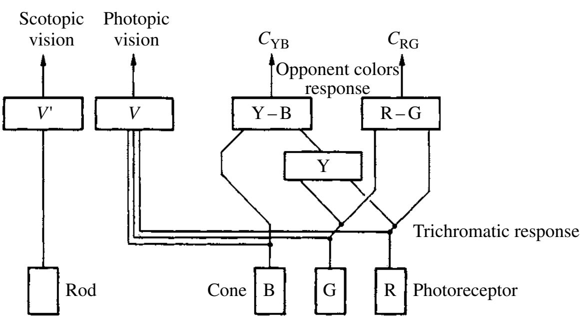

Figure 2.10 Color vision model based on stage theory (Vos and Walraven 1971). Reprinted from *Vision Res.*, **11**, J. J. Vos and P. L. Walraven, On the derivation of the foveal receptor primaries, 799–818. Copyright (1971) with permission from Elsevier

in the rods is directly related to the brightness response in scotopic vision, $V'(\lambda)$. The response from the three types of cones, R, G, and B, provide two opponent-color responses (R–G) and (Y–B) by synthesizing a yellow color (Y) from R and G, and then, as shown in Figure 2.10, by effecting subtraction of each of the signals. The brightness response $V(\lambda)$ in photopic vision is assumed to be synthesized by combining the outputs R, G, and B. It is believed that the rods do not function in photopic vision. However, according to a recent report, rods are found to be active to a luminance of about $500\,\mathrm{cd/m^2}$. Thus, color vision models based on the stage theory may see further progress in the future (Berman *et al.* 1987).

2.2 CHEMISTRY OF COLOR VISION

As previously described, the spectroscopic and psychophysical characteristics of vision are known, at least in outline. Whereas the mechanism of a phototube's response to light is entirely electronic, i.e., it is based on the photoelectric effect, the mechanism of the eye's response to light is photochemical, i.e., it is similar to photography. In photography, a photosensitized silver halide (AgCl, AgBr, or AgI) is converted into a silver image by a development process. Numerous chemicals are known to be suitable for the development. For example, if hydroquinone ($C_6H_6O_2$, H_2Q) is used as the chemical, silver ions Ag^+ combine with electrons e^- to yield metallic silver Ag according to a chemical reaction expressed by

$$\begin{aligned} H_2Q &\rightarrow Q + 2H^+ + 2e^- \\ Ag^+ + e^- &\rightarrow Ag \end{aligned} \tag{2.1}$$

In photography, a film, once developed, is no longer photosensitive. That is, a photographic film cannot be reused. However, an eye can be photosensitized repeatedly. The chemical reaction occurring in vision is far more complicated than that taking place in photography, and is distinguished in that it is a reproducible chemical reaction. The photosensitive substance in vision (corresponding to silver halide in photography) is known as a visual pigment. One visual pigment was identified about 100 years ago as a substance whose color fades when subjected to light. It was named visual purple according to its color. Visual purple is found not only in human vision. Similar pigments have been found in other animals. Figure 2.11 shows, for instance, the spectroscopic absorption for rods and cones of an ape, and Table 2.1 gives the absorption maxima of the visual pigments of other animals (Bowmaker