I  Color Vision in Art and Science
1. Aging through the Eyes of Monet

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1.1 Introduction

One of the most eventful periods for our understanding of color, both in art and in science, occurred between 14 November 1840 and 5 December 1926 - the life span of Oscar Claude Monet. In art, Monet's life encompassed the period between the Romantic pictorial tradition and Abstract Expressionism. In science, the physical principles pertaining to light and color laid down by Newton in the preceding century (Newton, 1704) were used to discover processes of color coding by the eye and brain. In short, the way both artists and scientists think about color today was shaped from 1840 to 1926 to a degree that may be unparalleled by any other period of 86 years.

Fig. 1.1: Claude Monet (1872) Impression: Soleil levant (Le Port du Havre par la brume). [Impression: Sunrise (Port of Le Havre Through the Mist.) Oil on canvas, 48 x 63 cm. (After restoration.) Musée Marmottan, Paris. (Photo credit: Giraudon/Art Resource, New York.)
Fig. 1.2: Pierre Auguste Renoir (1875-76) Torse de femme au soleil. [Torso of a Woman in the Sun.] Oil on canvas, 81 × 65 cm. Musée d’Orsay, Paris.
Art and science have at least one purpose in common: to enrich the human spirit. Whatever else one might say about Monet, he has certainly enriched our civilization. For when he unveiled the painting shown in Figure 1.1 at the first exhibition of the Société Anonyme des Artistes in 1874, he became the de facto leader of a movement that would alter the course of Western art history. This painting was originally called “The Port of Le Havre” but is now known by its subtitle “Impression: Sunrise,” from which a school of art was given its name, Impressionism. The picture captures what we now expect from an Impressionist painting—light, atmosphere, color and movement, all in the service of rendering the feelings of the moment.

The Impressionists were individualists, with different styles, preferred subject matter, and aspirations. What united them, however, was a rebellious spirit against the Paris Salon and a desire to capture the fleeting effects of light and color. Consider Pierre Auguste Renoir’s Torso of a Woman in the Sun (Fig. 1.2) presented in the second Impressionists’ exhibit in 1876. Although he preferred to paint the human form, he did so in a way that captured the delicate shades and shadows that were previously not recorded on canvas. But it was not just the handling of light and color that made the movement controversial; those pretty pictures of the Impressionists had said “No” to the classical pictorial tradition. Great art no longer had to depict kings, popes and saints; ordinary experience would do.

Someone once asked Renoir how it is that he obtained the delicate flesh tones of his nudes for which he became famous, and he said in effect, I just keep painting and painting until I feel like grabbing (Vollard 1925). When pushed further about the possible scientific basis of his techniques, Renoir said that if any of his work could be subjected to scientific analysis, he would not consider it art. Such a reaction is not atypical in the history of art, but it is somewhat atypical for the Impressionists. Many of them had a deep and abiding interest in color science. Camille Pissarro, for example, studied scientific literature in order to perfect his use of color.

The eyes of Monet changed over his life span, and so too did the way he portrayed the world. One must admit, of course, that changes in Monet’s vision are confounded by changes in his style of painting, notwithstanding that his stated goal was always to portray the subtle modulations of light without interpretation. Monet once said:

When you go out to paint, try to forget what objects you have before you, a tree, a house, a field or whatever. Merely think, here is a little square of blue, here an oblong of pink, here a streak of yellow, and paint it just as it looks to you, the exact color and shape, until it gives your own naive impression of the scene before you. (Perry, 1927, p. 120)

Monet’s changing portrayal of nature throughout his life has drawn attention to important processes of visual aging but has also perpetuated myths about the aging visual system. The purpose of this chapter is to offer a personal interpretation of color science and art in Monet’s lifetime, with an analysis of his aging eye as it may be derived from his art and as related to current research on senescence of human color vision.

1.2 A Link between Sunlight and Aging

Paul Cézanne once remarked (Barnes, 1990, p. 6) that “Monet is just an eye but my god what an eye!” The human eye is shown schematically in Figure 1.3. Light, if it is to be seen, must first travel through the various ocular media, the cornea, the anterior chamber filled with aqueous, the lens and the vitreous humor. It then passes through the layers of cells comprising the retina, shown in an enlarged view, where it can be absorbed by the rods and cones, the receptor cells that initiate vision.

The clinically normal eye appears rather stable over much of the life span. Barring disease or trauma, senescent deterioration is seldom noticed until mid- to late-life. At first glance, then, aging of the eye is a phenomenon of later life. Unfortunately, first impressions are quite misleading. A closer look at the visual system shows that it is constantly changing throughout life (Weale, 1982; Werner et al., 1990).
One factor that is believed to contribute to age-related changes in the eye is exposure to light itself (Werner, 1991). This factor may be especially pertinent to understanding Monet. Although other artists had painted in the open, Monet was perhaps the first to do so on a large scale and seemingly under all weather and seasonal conditions. His careful observations of the varying effects of sunlight and his insistence on painting en plein air virtually guaranteed that he would receive more than the usual cumulative exposure to sunlight. Even as early as 1867, at age 27, Monet had trouble with his vision following hours of painting in sunlight, and he received medical advice to abandon his outdoor painting (Stuckey, 1995). Several times thereafter he reported visual disturbances following a day of painting in the sun.

To understand the effects of light on the eye, it is necessary to define the spectrum of optical radiation. The visible spectrum includes wave-
Fig. 1.4: Extracted lenses of humans at various ages: (A) six months, (B) eight years, (C) 12 years, (D) 25 years, (E) 47 years, (F) 60 years, (G) 70 years, (H) 82 years, and (I) 91 years. Also shown are three types of cataractous lenses: (J) nuclear cataract, age 70; (K) cortical cataract, age 68; and (L) mixed nuclear and cortical cataract, age 74 years. (From Lerman, 1980.)
lengths between about 400 and 700 nm. At 400 nm the light normally appears violet in the light-adapted state, and shorter wavelengths are called ultraviolet (or UV) light. Because of absorption in the stratospheric ozone layer, very little light below 300 nm reaches the earth's surface so, for practical purposes, the UV spectrum of sunlight encompasses the range from approximately 300 to 400 nm. At the other end of the visible spectrum at 700 nm, the light normally appears red under light-adapted conditions; longer wavelengths are called infrared.

The energy contained within a single quantum is inversely related to its wavelength; quanta in the UV may contain enough energy to alter molecules in the eye that absorb them, primarily by initiating a cascade of oxidative reactions that are harmful to cells. This type of light damage is usually called photochemical or actinic (Werner and Spillmann, 1989). These photochemical reactions occur as long as we are exposed to high-energy photons and because we are exposed to them from birth, we can be assured that cellular deterioration, or senescence, begins even from the first days of life.

Experiments with nonhuman animals verify that any wavelength of light, in sufficient intensity, may damage the eye, but the shorter the wavelength, the more effective it is. For example, light at 325 nm in the UV is about 1,000-fold more effective in damaging the photoreceptors and retinal pigment epithelium than light at about 580 nm (usually appearing yellow) in the visible region of the spectrum (Ham et al., 1982). This damage is not funduscopically visible until about 48 hours after exposure, indicating that it is due to photochemical processes and not a burn. A retinal burn seldom occurs with natural light exposure because there is usually insufficient energy to raise the temperature of the retina by \( \geq 10^\circ C \), the approximate threshold for thermal damage. Exposures that are insufficient to reach the threshold for retinal damage may nevertheless add to the effects of other exposures, accumulating over time to produce cellular changes associated with normal aging (Marshall, 1985; Werner, 1991).

Under normal circumstances the eye has several natural defenses to protect it from the photochemical insult associated with sunlight. For example, distributed throughout the eye are various antioxidant molecules (e.g., superoxide dismutase, \( \alpha \)-tocopherol, glutathione, melanin, selenium and ascorbic acid) that neutralize phototoxic reactions. Especially important in this respect is the presence of the yellow macular pigment around the fovea (a depression in the retina where the cone photoreceptors are most densely packed and which provides our best spatial resolution; it typically corresponds to the center of gaze) which not only reduces the intensity of short-wave visible light reaching the retina, but which also consists of carotinoid pigments that are excellent at neutralizing some of the phototoxic reactions that occur in the eye (Kirschfeld, 1982). A second line of defense lies in the ability of cells to replace their parts by molecular renewal. Visual cells continuously reconstruct or replace virtually all of their parts except DNA (Young, 1982). As a result, damaged constituents of cells are replaced in a piecemeal fashion. A third defense against the most damaging wavelengths of light results from the tendency of these wavelengths to be absorbed by the ocular media, primarily the lens, before they can reach the retina. Figure 1.4 shows that the lens becomes an even more effective absorber of short wavelength light as an increasing function of age. One can see how clear the lens is in the newborn, and that it becomes distinctly yellow in adulthood and brown in old age. Quantitative studies with larger numbers of individuals reveal that the density (log of the reciprocal of transmission) of the ocular media increases as a function of age from infancy through the end of life (Werner, 1982; Weale, 1988; Pokorny and Smith, 1997).

Figure 1.4 illustrates common types of cataract. Nuclear cataract, which is what Claude Monet ultimately developed, is shown by lens J. Cataract is only an extreme of normal aging; we call the aged lens a cataract when it interferes with functional vision. Considerable experimental and epidemiological evidence has shown that lenticular senescence and cataract are, in part, due to the absorption of high-energy photons of UV (Young, 1991). In other words, exposure to sunlight accelerates aging of the lens and is one of the significant risk factors for cataract.
Once light reaches the retina, it can be absorbed by three different classes of cones, the photoreceptors of color vision. The foundation for our understanding of these processes was laid by James Clerk Maxwell and Hermann von Helmholtz in the mid 19th Century, although Thomas Young (1802) and others before him (Weale, 1957) had speculated earlier that normal human vision may be trichromatic. Maxwell and Helmholtz understood the difference between additive and subtractive light mixture, a distinction that would be discovered somewhat later by the Impressionists.

Subtractive mixture is familiar to most people through playing with paints in childhood. As illustrated by Figure 1.5, the mixture of blue and yellow paint typically appears green. In this example, the blue pigment absorbs many of the long-wave quantas and the yellow pigment absorbs many of the short-wave quanta. What reaches the eye is primarily middle wavelengths, the band that is reflected by both pigments. This is analogous to passing a white light with all wavelengths through two successive filters, a blue and a yellow. In Figure 1.5 the blue filter transmits quanta primarily of short and middle wavelengths while the yellow filter transmits primarily the middle and long wavelength quanta. Light of specific wavelengths is subtracted out at each stage and all that reaches the eye is that which both filters transmit, the middle wavelengths, which we usually call green. In subtractive color mixture the result is always a loss of light compared to that which would be transmitted (reflected) by either filter (pigment) alone. This can be appreciated by comparing the individual paint reflectances or the filter transmittances in the top row of Figure 1.5, with the resultant subtractive mixture shown on the right of the middle row.

Consider now a case of additive color mixture which can be effected using the same blue and yellow paints or filters shown in Figure 1.5. In the case of paints, a blue spot is placed next to a yellow spot so that light from each is reflected to the eye in parallel. If the spots are small enough, the two reflected lights will not be resolved as individual spots and will, in the words of Pointillist painters, "optically blend." The mixture in this example will appear achromatic (gray or white). The light distribution that reaches the eye in this example is equivalent to that obtained when the same broad-band light is passed in parallel through each filter so that both beams enter the eye and are superposed at the retina. The resulting mixture within the eye appears neither yellow nor blue, but achromatic. Such pairs of lights, that can be mixed to appear white, are called complementary lights. There is a large number of complementary light pairs, but they are most conveniently found using monochromatic lights, essentially single wavelengths of light (e.g., 470 and 570 nm). More generally, three relatively arbitrarily chosen lights are required to match any other light distribution. Physically different lights that appear identical are called metamers. The existence of metamers shows that the appearance of a color is not explainable on the basis of the physics of light alone, but is due to the processes that the light initiates in the eye and brain.

Maxwell's (1860) studies of additive light mixture carefully documented the proportions of three lights required to match an achromatic standard. He described the results by algebraic or color mixture equations, and because only three variables were required, he could illustrate the results in a triangular diagram. He realized that the trivariance of color mixture implies the existence of three kinds of color mechanisms in the eye. In related experiments, Helmholtz showed that any light of the spectrum can be matched by an appropriate combination of three others. From this observation, he too correctly concluded that the retinal receptors of daylight vision, the cones, are trivariant. Helmholtz's estimates of the relative sensitivities of the three cone types presented in his Handbuch der Physiologischen Optik (Helmholtz, 1867) are close to more modern estimates (Vos and Walraven, 1971; Smith and Pokorny, 1975) such as those shown in Figure 1.6 for infants and adults.

Although correct about this fundamental point, Helmholtz took another step that went beyond his data. To account for color appearance, he proposed that the response of each class of receptor is di-
Fig. 1.5: **Top row:** The number of quanta emitted from a hypothetical light source is plotted as a function of wavelength. Graphs in the middle and right show hypothetical paints and filters; the reflectance axes refer to the proportion of incident quanta (plotted from 0.0 to 1.0) reflected by the individual paints and the transmittance axes refer to the proportion of incident quanta (plotted from 0.0 to 1.0) transmitted by the individual filters. What is not reflected by the paint or transmitted by the filter is shown on the right axes as absorption (plotted from 1.0 to 0.0). A blue paint (filter) contains pigment that reflects (transmits) primarily short and middle wavelength quanta, but absorbs long wavelength quanta. A yellow paint (filter) contains pigment that reflects (transmits) quanta primarily at middle and long wavelengths, but absorbs short wavelength quanta.

**Middle row:** Subtractive mixture using the blue and yellow paints (in a uniform mixture) or the blue and yel-
1.3 The Trivariance of Color Mixture: Maxwell and Helmholtz

Fig. 1.6: Relative log quantal sensitivity of the three classes of human cone photoreceptor. Smooth functions show the sensitivities of short- (S), middle- (M) and long-wave (L) cones in the adult (Vos, 1978), adjusted in sensitivity according to the less dense ocular media (Werner, 1982) and absence of macular pigment of infants. Squares show sensitivity of S-cones from an infant obtained by Volbrecht and Werner (1987), while white and black circles show sensitivities of an infant’s M- and L-cones, respectively, obtained by Bieber et al. (in press).

Directly linked to perception. Therefore, he labeled the three classes of receptors as blue, green and red. For reasons to be described later, this aspect of his theory is not correct and it is more accurate to label the receptors according to their wavelength of maximal sensitivity at either short-, middle- or long-wavelengths.

Using psychophysical methods, Werner and Steele (1988) measured the sensitivity of the different cone pathways for 75 observers between the ages of 10 and 85 years. All three cone types were found to decrease significantly in sensitivity as a function of age. A linear function describes the data well and there is no statistical justification for supposing that the true function is non-linear over this age range. In addition, the rate of change with age appears to be similar for the three cone types; approximately 0.13 log unit (26%) per decade.

One can think of these results as showing that the elderly visual system, at least at this stage of pro-

low filters (in series) from the top row are illustrated. While these two figures show the approximate appearance with neutral adaptation, the figure on the right shows the physical light distribution reaching the eye from these mixtures.

**Bottom row:** Additive mixture occurs when the light is reflected by the two (unmixed) paints applied in small dots that cannot be resolved as discrete dots by the visual system; the appearance is achromatic. Additive mixture also occurs when the light is passed through the two filters in parallel; the appearance is achromatic. As illustrated by the graph on the right, the light reaching the eye is the sum of that reflected (transmitted) by each of the pigments (filters) alone.
cessing, is similar to the young visual system operating at a reduced light level.

Several sites in the visual pathway are responsible for age-related losses in sensitivity, but the largest proportion of the sensitivity loss appears to be at early stages of processing. These include increased absorption of light by the ocular media, a loss in the ability of the photoreceptors to capture quanta (Schefrin et al., 1992), and/or an elevation in neural noise (Schefrin et al., 1995).

One also sees a great deal of individual variation in cone sensitivity within each age. The sources of this variation are no doubt multi-faceted, but an important one is likely to be exposure to sunlight. Psychophysical studies (Werner et al., 1989) and an anatomical study (Marshall, 1978) suggest that retinal aging, as with aging of the lens, is accelerated by exposure to light, especially UV and short-wave visible light.

1.4 Monet’s Early Impressionistic Style

While Maxwell and Helmholtz were developing theories about the physiological basis of color mixing, Monet and Renoir were in La Grenouillère experimenting with additive and subtractive mixtures on canvas. Here, many of the fundamentals of Monet’s style were developed, including painting *en plein air* and representing complex aspects of reflections and shadow on canvas. More and more, his brushstrokes consisted of a pure, unmixed color, except when dark colors were formed through subtractive color mixtures.

In 1921, the Neo-Impressionist painter Paul Signac (1921) published an historical account that characterized Impressionism as based on these four aspects of technique:

**Fig. 1.7:** Claude Monet (1869) *La Grenouillère*. Oil on canvas, 74.6 x 99.7 cm. The Metropolitan Museum of Art, Bequest of Mrs. H.O. Havemeyer, 1929. The H.O. Havemeyer Collection.
1.4 Monet's Early Impressionist Style

1. Palette composed solely of pure colors approximating those of the solar spectrum;
2. Mixing on the palette and optical mixture;
3. Comma-shaped or swept-over brushstrokes;
4. Technique of instinct and inspiration.

All of these characteristics can be seen to some degree in Monet's 1869 painting, *La Grenouillère* (Fig. 1.7).

Signac's first point is clear, although the term "pure" is not necessarily used in any perceptual sense. He seems to have meant only that the Impressionists used the most saturated pigments available. The second point, mixing on the palette and optical mixture, refers to the use of subtractive and additive color mixture, respectively. This point is also related to the fourth point, which merely refers to an unwillingness of most Impressionists to follow strict divisionist techniques associated with Pointillism and Neo-Impressionism.

With respect to Signac's third point, Monet's comma-like brushstrokes can certainly be identified in many of his paintings. His brushstrokes, however, were quite varied (Seitz, 1956). He might use dapples of paint to represent the ripple of water, or swirls to depict smoke and steam. Multi-colored periodic patterns that recede in contrast and size are used in *La Grenouillère* to show shadows shimmering on the water. Or, as in some of his water lily paintings, Monet captures shadows reflected on the water with mostly vertical lines, while the lily pads are contrasted with thick horizontal brushstrokes. These and other brushstrokes were combined with a variety of textures (Herbert, 1979) which were also quite complex, but which generally varied from coarse in the foreground to fine in the background, corresponding to the surface variations on the retinal image. At times criticized as unskilled, some of the patterns seen in his 1869 *La Grenouillère* may be considered a prelude to abstract art.

Close inspection of Monet's paintings also shows another interesting feature – the weave of his white canvases can often be seen through the background because they are not completely covered by paint. The choice of a white canvas was not accidental. Canvas was available in a variety of colors in the 19th Century, but Monet always used white (Cullen, 1982). Unpainted areas provided contrasting textures, and the high reflectance of a white canvas could be exploited to capture quickly certain highlights in natural scenes by having to apply little or no paint.

Monet described still another reason for his choice of a white canvas; he said it was to establish a scale of (color) values. He studied the light intensely and is said to have attempted to understand the color of the prevailing illumination before attempting to evaluate the colors of the landscape. Our sense of illumination was later discussed by the Gestalt psychologist David Katz (1911), but it is still poorly understood.

In describing this period of his life when he and Renoir, among others, would paint together, Monet said, "It was as if a veil was torn from my eyes and I understood what painting could be" (Barnes, 1990, p. 8). Soon, however, another veil would be torn from Monet's eyes when in 1870 he and his wife, Camille, moved to London. He wanted to escape conscription in the Franco-Prussian war as did Pissarro, whom he met there. In London, Monet and Pissarro saw the works of that lone English genius, J.M.W. Turner, almost certainly one of England's most creative painters.

1.4.1 Possible Influences of Turner and Goethe

Not only Monet and Pissarro, but many of the budding Impressionists went to London to see, for example, Turner's *The Fighting Temeraire* (1838) and his *Rain, Steam and Speed* (1844). Captivated by light and color, Turner attempted to achieve in his paintings a luminosity and brightness that approached those visual experiences where light and color reach their highest levels of complexity for the painter – when light is reflected from water or seen through rain, steam and fog.

How did he do it? First of all, he seemed to grasp the difference between additive and subtractive color mixture. In many of his paintings Turner strategically placed small dots of light color so that the additive mixture provided luster and brilliance. This was about 40 years before the Impressionists would exploit this technique more fully, and some 50 years before the Neo-
Impressionists would carry it to its limit. Turner also experimented extensively with blocks of color placed side-by-side to study the ways colors influenced each other (Clark, 1960).

Despite having very little formal education, Turner painstakingly worked his way through a translation of Johann Wolfgang von Goethe’s (1810) *Zur Farbenlehre* (Reynolds, 1969). To appreciate the impact of Goethe on Turner, it is necessary to describe briefly ideas of Goethe that have taken hold.

Goethe wanted to be a painter, but lacked the
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Many modern scientists dismiss his *Farbenlehre* because of his polemic against Newton; history does not look kindly on attacks against Newton. Nevertheless, there is much in Goethe’s book that is worthwhile, beginning with his attempt to analyze sensations independently of the stimuli that produce those sensations. His statement that “the theory of colors in strictness may be investigated quite independently of optics” (Goethe, 1810, p. 163) anticipated an oft-quoted statement by Maxwell (1872) who asserted that “the science of color must ... be regarded as essentially a mental science” (p. 261). Goethe also anticipated Hering’s opponent-color theory (described below) when he indicated that there are pairs of primary colors (at least four, perhaps six) and that the paired members interact with each other antagonistically. He came to this view by careful observations of afterimages, successive contrast effects, as he describes in the following example:

I have entered an inn toward evening, and, as a well-favoured girl, with a brilliantly fair complexion, black hair, and a scarlet bodice, came into the room, I looked attentively at her as she stood before me at some distance in half shadow. As she presently afterward turned away, I saw on the white wall, which was now before me, a black surrounded with a bright light, while the dress of the perfectly distinct figure appeared a beautiful sea-green. (Goethe, 1810, p. 83)

Goethe painted the negative image shown in Figure 1.8 so that this “well-favoured girl” can be appreciated in all her splendor through an afterimage. To produce the afterimage, carefully fixate a salient point and hold the eyes steady for about 15 seconds; then shift your gaze to a blank field such as a neutral wall. It helps to blink when looking at the blank field. Notice that the colors of the afterimage are complementary, or approximately so, to those of the original image.

Goethe described analogous phenomena in the spatial domain based on colored shadows, a topic that would later engage Helmholtz and Hering (Hering, 1887) in heated debate. According to Goethe’s illustration, shown in Figure 1.9, a surface is illuminated by a whitish light from the left and a yellowish light from the right. Each beam will be partially obstructed by the object in the center, resulting in a shadow on either side. The shadow on the right is lacking the whitish light so, having only the yellow illumination, it appears a more saturated yellow than the surround. One might expect that the shadow on the left, lacking the yellowish light and being illuminated only by the whitish light, would appear white, but it does not. Rather, it appears bluish, that is, tinged with the opposite hue to that surrounding it. This is an example of what is more generally known as simultaneous contrast. As Goethe correctly concluded from this phenomenon, blue and yellow oppose each other not just in time, as with afterimages, but also in space.

Goethe described how perceptual principles could be exploited to good effect in painting. Turner accepted this view and used it to his advantage to exaggerate light yellow areas by surrounding them with dark blue areas. In a tribute to Goethe, he painted *Light and Colour (Goethe’s Theory) – The Morning after the Deluge* (Fig. 1.10). This painting is predominantly yellow, the color that Goethe considered the first derivative of light. It stands in marked contrast to Turner’s (1843) companion painting (*Shade and Darkness – The Evening of the Deluge*) which is dominated by blue, Goethe’s first derivative of darkness. At this point, Turner had obviously become extremely abstract, anticipating aspects of Impressionism and Expressionism. This work is without precedent in Western Art and it is safe to say that Monet could not have seen anything remotely similar to it in Europe at the time.

Turner also became quite a profound pessimist.
as exemplified by the verses attached to the title of this painting taken from his poem, *The Fallacies of Hope*. He wrote: “hope, hope, where is thy market now?” This aspect of Turner would not have appealed to the Impressionists. Renoir said he simply wanted to paint pretty pictures. And Vincent van Gogh, more a Post-Impressionist, said that he hoped that their art could “give comfort, and make life possible, in the way that Christianity once did” (Russell, 1974, p. 22).

Pissarro was enthralled with Turner, and although Monet rarely commented on other paintings, he did make complimentary statements about *Rain, Steam and Speed* (interestingly, an etching of this Turner masterpiece by Félix Bracquemond was shown in the first Impressionist exhibit). Generally, however, Monet denied being much impressed by Turner and was critical of his exuberant romanticism. In truth, Paul Signac noted that the Impressionists studied Turner’s work and mur-

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**Fig. 1.10:** Joseph Mallord William Turner (1843) *Light and Colour (Goethe’s Theory) – the morning after the Deluge – Moses writing the Book of Genesis.* Oil on canvas, 78.8 x 78.8 cm. Tate Gallery, London.
1.4 Monet’s Early Impressionistic Style

1.4.1 Revealing Snow and Ice Effects

Monet’s early Impressionistic style was characterized by a new approach to depicting natural effects, particularly those related to light and atmosphere. Signac (1921) described how Monet succeeded in producing the sensation of whiteness of the snow, something that previous artists had not been able to achieve. Signac writes:

"They were in the first place struck by his snow and ice effects. They were astonished to see how he had succeeded in producing the sensation of whiteness of the snow while they had so far been unable to achieve this with their large patches of ceruse (white lead) spread out flat with broad brushstrokes. They say that this marvelous result was obtained not by a uniform white, but by a number of touches of diverse colors, placed side by side and reconstituting the desired effect at a distance. (pp. 239-240)"

Turner and Monet had much in common besides their interest in additive color mixture and color contrast effects. They were both fascinated by the changing effects of light at different times of day. John Ruskin (1843) catalogued some 60 Turner paintings according to the lighting conditions associated with various times of day, as modified by weather, atmosphere and the objects themselves. Later, Monet would illustrate the changing effects of light and atmosphere in more compelling fashion through series of paintings of the same subject. Both artists went to great extremes to observe nature. For example, Turner claimed to have tied himself to the deck of a ship to observe a raging storm at sea and was nearly killed. Monet described a similar experience. But their differences were equally compelling; while Turner depicted nature in her fury, Monet seems to have preferred her more pastoral, but elegant, simplicity.

1.4.2 Possible Influences of Chevreul and Delacroix

If Monet had been inclined to study the work of any scientist, it would probably have been Michel Eugène Chevreul rather than Goethe. Whereas an emotion-laden analysis of color appealed to Turner and Goethe, a less passionate analysis appealed to Chevreul and Monet. Chevreul was the Director of Dyes for the Gobelins tapestry works, and in that capacity he conducted detailed experiments on the interactions between threads placed side by side, either when the colored regions were small enough to mix additively or large enough to create simultaneous contrast. These experiments are described in his 1839 book (Chevreul, 1839), *De la Loi du Contraste Simultané des Couleurs*, a book that was hailed by the Impressionists and studied by Helmholtz. Chevreul’s studies of contrast culminated in a set of descriptive laws. Figure 1.11 shows one of his beautiful illustrations of how a hue induces its complement in surrounding regions, analogously to Goethe’s colored shadows.

Many of Chevreul’s ideas were tested on the canvas by Eugène Delacroix. Like Turner, Delacroix offended his contemporaries by his bold use of color, although it is doubtful that his paintings ever realized the luminosity of Turner’s. Figure 1.12 shows his painting called *The Lion Hunt* (1860-61). The carnage in Delacroix’s picture is made vivid enough by his use of saturated pigments, and perhaps it is done so well because it was said that he never missed a feeding at the Paris zoo (Clark, 1960). The Impressionists studied the work of Delacroix and seemed particularly enamored by his thoughts on simultaneous contrast, about which he is said to have remarked: “Give me the mud of the streets and I will turn it into the luscious flesh of a woman” (Signac, 1921, p. 238) (if you will allow me to surround it as I please).

If it is assumed for the moment that the “luscious flesh” that Delacroix had in mind was white, it can be shown by experiment that he was correct. Figure 1.13 presents results from an experiment (Werner and Walraven, 1982) in the CIE x,y chromaticity diagram, which represents all possible additive color mixtures. The perimeter of the diagram represents the loci of monochromatic lights and the light mixtures (between 400 and 700 nm) that enclose the space. The colored areas illustrate the approximate appearance of these light mixtures in the neutral state of adaptation (i.e., when the colors are viewed in an unilluminated surround). The subject’s task in the experiment was to vary the ratio of two lights (complementary colors) until the mixture looked white. The central x shows the light mixture that appeared white without any background or surrounding light. The experiment was then repeated in the presence of various larger chromatic adapting backgrounds. The spokes connect the neutral white point and the adapting backgrounds, which were all located on the perimeter of the color dia-
Fig. 1.11: M. E. Chevreul's (Chevreul, 1839) illustration of simultaneous hue contrast. In this figure, the colors that would normally be induced by a colored disk into a neutral surround are exaggerated by painting the surround regions. (Colors are digitally enhanced by the author to compensate for fading of the original plate.)

The data points show the stimulus that looked white after adaptation to various colors and for various contrasts (i.e., intensity ratios of test and background). The dashed contours are model predictions assuming von Kries adaptation and a subtractive process; that is, separate sensitivity adjustments in each class of receptor in proportion to their activation by the background light (Werner...
and Walraven, 1982; see chapter 12). Without discussing the experimental details, one can readily appreciate that Delacroix was correct: that any light can appear white under the right conditions of contrast and adaptation.

Delacroix also advocated the use of hatchings to influence colors based on a complementary phenomenon to contrast called assimilation or the Bezold Spreading Effect (Bezold, 1874). This occurs when a background and interlaced pattern of different color fail to oppose each other as in simultaneous contrast, but seem to blend together. Figure 1.14 illustrates assimilation with four different hues that have black or white hatching superimposed; although the background hue within each panel is physically uniform, it appears different depending on whether it is interlaced with black or white.

Assimilation is still not well understood, but it is known that it cannot be explained by light scatter from one region of the image to another. When the hatching is fine relative to the diameters of individual receptors, additive light mixture occurs, but in this case the hatching itself will not be visible. If the elements in the hatching are small relative to the postreceptoral elements that sum inputs from a number of cones, assimilation may occur. When the hatching is courser, contrast typically occurs, but depends on a number of factors such as the luminance of the pattern relative to the background (de Weert and Spillmann, 1995). By varying the viewing distance of a suitable pattern, one can observe light mixture, assimilation and contrast. Thus, assimilation, although not due to optical mixture, could be due to a neural blending in some color channels.
Fig. 1.13: The loci of lights that appear white under various states of adaptation presented in the CIE x,y chromaticity diagram. Colored areas within the diagram represent the approximate appearance of additive color mixtures in a neutral state of adaptation. The central x represents the light mixture that appeared white in a neutral state of adaptation for one observer, while the data points show the chromaticity of the light that appeared white following adaptation to the continuously presented chromatic backgrounds (250 Troland retinal illuminance). The backgrounds tested are all on the perimeter of the diagram and connected to the central x by lines. Squares, triangles and circles represent illuminance contrasts (test/background intensity) of 0.2, 1.0 and 5.0, respectively. (After Werner and Walraven, 1982.)
1.4 Monet's Early Impressionistic Style

Fig. 1.14: Illustration of assimilation or the Bezold Spreading Effect. The background color is the same within a panel, but it appears darker when interlaced with black hatching compared to when it is interlaced with white hatching.

While other color channels still respond differently to the form and the background (Jameson and Hurvich, 1989). Assimilation probably occurs as much in nature as contrast, but we know much less about its physiological basis (de Weert, 1991).

It may seem from these phenomena of adaptation, assimilation and contrast that the visual system is easily fooled and subject to illusion, but the mechanisms producing these effects are what make normal color vision possible. As Hering (1920) pointed out:

"The most important consequences of reciprocal interactions are not at all those expressed in contrast phenomena, that is, in the alleged false seeing of 'real' colors of objects. On the contrary, it is precisely the so-called correct seeing of these colors that depends in its very essence on such reciprocal interactions" (pp. 123–124).

In full agreement, Monet would later say:

For me, a landscape does not exist in its own right, since its appearance changes at every moment; but its surroundings bring it to life – the air and the light which vary continually ... For me, it is only the surrounding atmosphere which gives objects their true value. (Barnes, 1990, p. 36)

Thus, while some of these phenomena of adaptation, assimilation and contrast do illustrate imperfect color constancy, they seldom lead to confusion about an object's identity based on color. More generally, they support correct identification of object color by accentuating differences between object
Fig. 1.15: Top: Claude Monet (1873) *Les coquelicots à Argenteuil* [Poppies at Argenteuil.] Oil on canvas, 50 × 65 cm. Musée d’Orsay, Paris. (Photo credit: Erich Lessing/Art Resource, New York.)

**Bottom:** Claude Monet (1879) *Camille Monet sur son lit de Mort* [Camille Monet on her death-bed.] Oil on canvas, 90 × 68 cm. Musée d’Orsay, Paris.
and shadow, with assimilation enhancing the uniformity of a single surface and contrast enhancing differences between figure and ground. These examples provide important probes to visual scientists for identifying properties of the visual system that are normally not apparent at all. The mechanisms mediating these effects are what keep us from being fooled most of the time about the reflectance or color of objects when the color of the illumination changes – they make color constancy possible. This refers to the experience that the colors of most objects appear to be about the same in a wide variety of lighting conditions, even though they may reflect very different spectral distributions to the eye. Color constancy would not be possible if the visual system were not able to adjust its chromatic sensitivity as illumination varies.

1.5 Monet’s Years in Argenteuil and Vetheuil

Monet lived in Argenteuil and Vetheuil from 1871 to 1881. During this time he created some of the most beloved masterpieces of the Impressionist movement. Many of these paintings illustrate an idyllic country lifestyle with his wife Camille and young son Jean, such as in his painting, The Luncheon (1873) or the Poppies at Argenteuil (Fig. 1.15, top). This was a happy time for Monet – until 1879 when his wife Camille died. Out of this tragedy we gain insight into Monet’s seemingly irrepressible obsession with the changing effects of color. He went so far as to portray Camille’s changing coloration on her death bed (Fig. 1.15, bottom) and described his feelings as follows:

You cannot know ... the obsession, the joy, the torment of my days. To the point that, one day, when I was at the death-bed of a lady who had been, and still was, very dear to me, I found myself staring at the tragic countenance, automatically trying to identify the sequence, the proportions of light and shade in the colors that death had imposed on the immobile face. Shades of blue, yellow, gray, and I don’t know what. That’s what I had become (Clemenceau, 1929, p. 350–351).

1.6 The Opponent Code for Color Appearance: Hering

During these years, Germany was developing its own Impressionist school through the wonderful paintings of Adolph Menzel, Max Liebermann, Gotthardt Kuehl and others (Düchting and Sagner-Düchting, 1993), although the most significant events from the point of view of this essay were probably being carried out in the laboratory.

Ewald Hering, Professor of Physiology in Vienna and later in Prague and Leipzig, pointed out that the Helmholtz view nicely accounted for the trivariance of color mixture, but the second part of the Helmholtz theory – that there are three fundamental hue sensations – is inconsistent with our color experience. Hering (1920) proposed that there are four elemental hues, red, green, yellow and blue, and that all hue experience is based on combinations of these elements. (For a complete account of color experience, Hering also proposed that there are two fundamental achromatic colors, black and white; see chapter 10, Shinomori et al., 1997.) He was not the first to make this proposal. It could be pointed out that Leonardo appreciated this centuries before. To which Hering replied that:

“If one were to designate the nomenclature used ... as a four-color theory, then ... language itself would be its author, for language has long since singled out red, yellow, green and blue as the principle colors of the multiplicity of chromatic colors” (Hering, 1920, p. 48).

Hering further postulated that the hue variables are organized physiologically in antagonistic pairs that involve processes of excitation and inhibition, with the result that the sensations of red and green never occur at the same time and place, nor do the sensations of blue and yellow. He, therefore, referred to these paired colors as opponent. To explain phenomena of successive and simultaneous contrast, Hering also proposed that these physiological processes are organized in an antagonistic or opponent fashion across time and space.

Since Berlin and Kay’s (1969) anthropological survey, evidence has supported the view that there are a limited number of hue names needed to describe our color experience and that they are de-
dependent on the organization of neurophysiological mechanisms in the eye and brain (Ratliff, 1976). One example is shown in Figure 1.16. Observers were asked to describe lights of different wavelength using the terms red, green, yellow and blue (Werner and Wooten, 1979). Results are shown by the white squares. Red or green is plotted from 0 to 100% on the left axis, and blue or yellow is plotted in the opposite direction, from 100 to 0%, on the right axis. The data could be plotted in this way because, consistent with Hering's theory, the observers almost never used the terms red and green together or the terms blue and yellow together. The letters (B, G, Y) on the horizontal axes designate the wavelengths of the lights that were uniquely blue, green or yellow for the average of the same three persons whose hue-naming data are presented.

Jameson and Hurvich (1955) developed methods to measure psychophysically the opponent processes of Hering using a hue-cancellation task. The strength of each hue (e.g., red) was quantified by the energy of the opponent hue (e.g., green) necessary to produce an equilibrium state (e.g., neither red nor green). Hue cancellation functions presented in Figure 1.17, based on their method, show the response of the red-green and yellow-blue opponent channels as a function of wavelength. Responses of single cells of the macaque monkey at various levels of visual processing look remarkably similar to these functions (see chapter 3; Zrenner et al., 1990), and there is compelling reason to believe that these opponent processes, via cortically-rectified signals (DeValois and DeValois, 1993), are an important part of the neural network responsible for perceived hue. Figure 1.16 (circles) compares hue naming and the mean ratio of red-green to yellow-blue response at each wavelength measured by the cancellation task. The opponent responses measured by cancellation agree quite well with color naming, consistent with the idea that these opponent processes are the neural substrate of color appearance.

While some researchers, even as recently as 20 years ago, seemed to find the Hering view incompatible with the Maxwell-Helmholtz theory,
The opponent code for color appearance: Hering

Fig. 1.17: Opponent-hue cancellation functions averaged for three observers plotted as a function of wavelength. Red-green is shown by white squares, with red plotted as positive and green as negative. Blue-yellow is shown by black circles, with blue plotted as negative and yellow as positive. (After Werner and Wooten, 1979.)

Johannes von Kries (1882), Professor of Physiology in Freiburg, put forth a zone theory before the turn of the century in which color vision begins with the activity of three classes of cone photoreceptor which is re-mapped onto the neural-opponent processes of Hering. A more modern version of such a zone model based on equations of Jameson and Hurvich (1968) is presented in Figure 1.18. It utilizes the idea that receptors activate neural processes in either an excitatory or inhibitory fashion, and different combinations of all three receptors produce the two opponent-chromatic processes. The direct connections between receptors and opponent mechanisms shown in Figure 1.18 are a considerable oversimplification to illustrate functional relations. Anatomical and physiological studies have demonstrated numerous interactions between cells at various levels between the photoreceptors and higher-level color mechanisms. It should also be noted that more complex non-linear models are required to describe some aspects of color perception, even though the linear equations used in Figure 1.18 provide an excellent first-order description of cancellation functions.

The data on age-related changes in color vision presented so far have dealt only with the first zone (i.e., photoreceptors), but there might also be age-related changes in the later stages of color processing. Schefrin and Werner (1990) measured the balance points of the opponent mechanisms (that is, the spectral unique hues) in 50 observers ranging in age from 13 to 74 years. Of particular interest are the loci of unique blue and unique yellow, because they can be described under many conditions by a linear model and will, therefore, be unaffected by age-related losses in light intensity associated with lenticular senescence. The results show that there is no significant change in the wavelength of these unique hues over this wide age range. That these results reflect a more general pattern of stability in color perception across the life span was confirmed in a color-naming experiment using more naturalistic, broad-band surfaces, color chips from the Uniform Color Samples of the Optical Society of America (Schefrin and Werner, 1993). Not only did young and old use the same words to describe hues, but they did not differ significantly in the proportions of different
1. Aging through the Eyes of Monet

Fig. 1.18: A modern version of von Kries's 1882 zone theory (Kries, 1882), based on the equations of Jameson and Hurvich (1968) linking the activity of the three classes of cone photoreceptors (S, M and L) to red-green (left) and yellow-blue (right) opponent mechanisms as a function of wavelength from 400 to 700 nm. The shapes of the opponent-response functions depend on the sign (+ or -, corresponding to neural excitation or inhibition) of the signals from the cones and their neural weights. The parameters (specified in terms of quanta at the cornea) and equations used to generate the functions are shown at the bottom.

Fig. 1.19: Heterochromatic brightness sensitivity change per decade is plotted as a function of wavelength at the cornea (black circles) and at the retina (white squares). The horizontal line at zero denotes no age-related change. The thicker horizontal line at +0.05 shows the mean increase in brightness sensitivity per decade between 420 and 560 nm. (After Kraft and Werner, 1994.)
1.7 Monet’s Response to Pointillism and Divisionism

In the eighth Impressionist exhibit in 1886, Georges Seurat showed how the Neo-Impressionists would take the next step in applying the color science of the time to painting. His (1884) *A Sunday Afternoon on the Island of the Grand Jatte* (Fig. 1.20) is one of the most celebrated examples of the technique of Pointillism. The technique is, in principle, not different from that used by Turner, although in practice it was an extraordinary leap from Turner because the points were applied by Seurat in a much more systematic and consistent manner. Seurat had studied all the color science available to him including work by Chevreul and Helmholtz. His masterpiece includes dots of varying sizes to achieve the Pointillist goal of increasing the luminosity of paintings by placing small dots of pure color side-by-side to produce an optical mixture in the eye or to achieve strong hue contrasts with larger dots.

Pissarro, van Gogh and Matisse tried their hand at Pointillism but were not satisfied and soon abandoned the technique. Their disillusionment was due, in part, to the fact that the appearance of a Pointillist painting depends so critically on the viewing distance. At some distances, the paintings do not have the brilliant hues intended, but just the opposite—the hues appear drab and desaturated. Even Seurat’s (1887–88) *Les Poseuses*, with its tiny dots, is a disappointment in this regard (Ratliff, 1992). Interestingly, the mechanism that underlies the success of the Pointillist technique as an art form also underlies its limitations. The problem arises because the signals from cone photoreceptors are integrated in the visual pathways to form receptive fields, areas of the retina that activate a particular cell by excitation or inhibition, depending on where the light falls within the receptive field (Wiesel and Hubel, 1966), as illustrated by Figure 1.21. The three-dimensional profile on the left illustrates the response increase when stimulated by green in the receptive field center and the inhibition by red in its surround. The other cell shown has a blue-yellow, antagonistic center-surround organization. These receptive field profiles are spatial filters for color processing, modeled here as the difference of two Gaussian functions, one representing the distribution of excitation and a second, having lower amplitude but broader area, representing the distribution of inhibition. Many individual cells can be modeled in this way, although their responses often do not follow the perceptual red-green or blue-yellow axes (Lennie and D'Zmura, 1988). Nevertheless, the combined activity of many such cells having overlapping receptive fields appears to result in a network that forms...
a mosaic consistent with Figure 1.21. Such receptive fields provide the kind of mechanism required to explain the spatial-chromatic opponency described by Hering (1920). Of course, each individual receptive field will produce a response only to stimulation by an edge, but if the entire receptive field is uniformly illuminated by a particular color it will not respond. These receptive fields help to explain hue contrast at borders, but not the induction of hue across large areas of the visual field such as observed with Goethe’s colored shadows. How an entire area is filled-in perceptually with a uniform hue is not clear, although a number of neurophysiological hypotheses involving propagation across cortical regions beyond the area of the classical receptive field have been described (Spillmann and Werner, 1996).

Consider the consequences of this kind of neural organization for how we perceive a Pointillist painting. Suppose an artist places small dots of paint, say a blue and yellow dot, side-by-side. If the dots, at a particular viewing distance, are small enough to approach the size of individual cone receptors, additive color mixture would be expected and the region would appear achromatic. If the dots were somewhat larger, but small enough so that the yellow and blue fell within the excitatory and inhibitory regions of the receptive field, respectively, they would likely cancel each other’s effects, rather than produce contrast. The result would be an achromatic color. Notice that in this case, the effect is similar to additive color mixture, but it is really a neural mixture that depends on the size of the areas over which information is summed in the visual pathways. Whether small dabs of paint produce cancellation, contrast or assimilation depends upon the “fit” between the size of the dots imaged on the retina (and hence the viewing distance) and the size of the receptive fields. Receptive fields are known to increase in size with retinal eccentricity, although there is a range of receptive field sizes representing each re-
1.7 Monet’s Response to Pointillism and Divisionism

Fig. 1.21: Receptive field profiles for red-green and blue-yellow cells. These cells have an antagonistic center-surround spatial organization such that one color in the center produces excitation and the opponent color in the surround produces inhibition.

The Neo-Impressionists did not know about receptive fields, but certainly knew about the perceptual phenomena that they produce. At just the right distance, the receptive fields will be activated to produce the additive mixtures and contrasts intended by the artist. How does one know what that distance is? In noting that the brilliance of Pointillist paintings depended on the viewing distance, Pissarro suggested the general rule that a Pointillist painting be viewed at a distance that is three times the diagonal. Of course, this advice only makes sense if the size of the dots has a fixed relation to the size of the painting as a whole (Weale, 1971) - which was apparently not always the case.

Paul Signac emphasized that the best technique practiced by Neo-Impressionists was “Divisionism” not “Pointillism,” by which he meant that the paint should be applied with small distinctive strokes, not tiny points. Signac wrote: “The Neo-Impressionist does not paint with dots, he divides” (1921, p. 207). It is difficult to see how this solves the problem; rather, it only defines a new set of distances at which one has hue cancellation vs. contrast. Perhaps anticipating this rejoinder, Signac referred to Rembrandt:

“A painting is not to be sniffed,” said Rembrandt. When listening to a symphony, one does not sit in the midst of the brass, but in the place where the sounds of the different instruments blend into the harmony desired by the composer. Afterwards one can enjoy dissecting the score, note by note, and so study the manner of orchestration. Likewise, when viewing a divided painting, one should first stand far enough away to obtain the impression as a whole, and then come closer in order to study the interplay of the colored elements, supposing that these technical details are of interest. (Signac, 1921, p. 264).

In the meantime, Monet tried other approaches that used elements of Divisionism, but without a rigid application of the technique. One example is shown in Figure 1.22, Bend in the Epte River near...
Giverny (1888). The foliage of the trees follows very much the style of Seurat, but it is set apart from the water and sky which maintain his comma-like strokes. The result is just as luminous as the Pointillist and Divisionist attempts, but seems altogether more spontaneous and natural.

1.8 Hay Stack and Cathedral Series

By 1890, at the age of 50, Monet had reached a high standing in the art world and had found financial security. He rebuilt an old farmhouse in Giverny and employed six gardeners to indulge his love of horticulture and flowers. It was a magnificent site which he captured in numerous paintings. Glorious though his gardens were, Monet also illustrated the subtle undulations of light and color in more mundane spots such as in the hay stacks behind his house. There he painted a series of canvases capturing different conditions of light, atmosphere and weather. His approach was methodical; rising early in the morning even in the depth of winter, he caught the first glimpse of sunrise at his chosen location, typically rested at midday and then returned to catch the setting sun.

Figure 1.23 shows how splendidly Monet captures the light in the hay stacks. On the top, the morning light falls upon the snow, and the yellow hay stacks are surrounded with the blue colored shadows described by Goethe. On the bottom, Monet shows a greenish shadow induced by the reddish color of the


Bottom: Claude Monet (1890–91) Meule. Soleil couchant. [Hay Stack. (Sunset).] Oil on canvas, 73.3 × 92.6 cm. Juliana Cheney Edwards Collection, Museum of Fine Arts, Boston.
Fig. 1.24: **Left:** Claude Monet (1894) *Le portail, brouillard matinal.* [Rouen Cathedral: The Portal (Early Morning).] Oil on canvas, 100 × 65 cm. Museum Folkwang, Essen.  
**Right:** Claude Monet (1894) *Le portail (soleil).* [Rouen Cathedral: The Portal (Early Afternoon).] Oil on canvas, 100 × 65 cm. Board of Trustees's, National Gallery of Art, Washington.

Monet’s hay stack series includes more than 30 canvases, from different vantage points and distances, and in different lighting. In order to depict fugitive effects, he worked on as many as seven canvases simultaneously, apparently dashing from one to another as the light would change. The canvases would then be taken to the studio and placed side-by-side for retouching. The series was intended to be displayed together. That the subject matter is monotonous and uninspiring to many people is beside the point. Monet said: “I was trying to do the impossible ... to paint light itself” (Myers, 1990, p. 92).

Hay stack in the late afternoon sun. We now regard this simultaneous contrast effect, exaggerated by Monet on the canvas, as due to the reciprocal neural-opponent responses across the visual field.

Monet painted several other series, including the Gare St. Lazare, the Seine near Giverny and various scenes from his gardens. In the cold winter of 1892, the 52-year-old Monet rented a large room directly across from the Cathedral of Notre Dame in the nearby city of Rouen. For the first time, he would paint an outdoor scene from indoors. Unlike many cathedrals, there was little space to afford an unobstructed vantage point so we see the cathedral facade cropped (Fig. 1.24), due apparently to the restricted view through the window. Monet was apparently frustrated, not so much from the view, but from what he was trying to accomplish. No other paintings occupied so much of his time.

He left Rouen after the winter and returned again the next year, but still failed to complete his project.
until he returned home and painted from memory. In all, he managed 30 canvases which he placed side-by-side in his studio to finish. They all are signed 1894, the year of their completion. Once again, the content of the series is not particularly critical to Monet (cf., Pissarro, 1990). Each canvas represents a moment in time associated with different light and atmosphere. In Figure 1.24, the painting on the left represents early morning, and the sun can be seen gently breaking through the mist near the spires while the light is occluded nearer the ground. On the right, it is afternoon, and the entire facade basks in the sunlight. The shadows are created with sculpted mounds of paint, whereas the bright areas include patches where the canvas is not completely covered.

If Monet had wanted to represent the physical situation accurately he would have had to make the afternoon scene reflect several thousand times more light to the eye compared to the canvas depicting the morning scene. He could not have done that, but he didn’t need to because our visual system is remarkably insensitive to ambient light level over a large range. How, then, does his painting convey the obvious impression that the afternoon scene is much brighter than the morning scene when there is relatively little difference between the two paintings in their average light reflectance?

Monet seems to have discovered another fundamental characteristic of the visual system. As the overall light level increases, so does the perceived contrast - yellows and blues become more yellow or blue, blacks become blacker and whites become whiter. The loss of sensitivity to absolute light level may result largely from sensitivity adjustments of the cone pathways, but the changes in contrast require an explanation at a neural level in the opponent pathways (Jameson and Hurvich, 1975).

1.9 Monet Returns to London

In the fall of 1899, Monet traveled back to London. From the Savoy Hotel and St. Thomas’s Hospital he would paint Waterloo Bridge and the Houses of Parliament. He made several trips over the next five years, during which he completed more than 100 canvases (Tucker, 1995). It is interesting to compare his Boats on the Thames in 1871 with his Houses of Parliament painted 30 years later (Fig. 1.25). The atmosphere in the latter is richer, as we see the fiery sun barely penetrating the dense clouds. Indeed, the pageant of colors in many canvases from this series anticipated Fauvism. It is almost as though Monet is now challenging Turner on his own turf, as Turner had once done with the great French landscapist, Claude Lorrain. Turner not only copied some of Lorrain’s paintings, but insisted in his bequest to the National Gallery that his copies hang next to Lorrain’s originals for comparison, a request that is still honored. Some critics pointed out that now Monet’s paintings should be hung next to Turner’s, calling them both great Impressionists worthy of comparison (Gage, 1972).

1.10 Water Lilies and Cataracts

Monet’s final motif, which occupied him for well over 25 years, was based on his garden at Giverny, particularly his water lilies and his Japanese-style bridge. The bridge on the top in Figure 1.26 was painted in 1899 and the one on the bottom about 20 years later. What was the basis for the enormous difference? In the intervening years, Monet’s cataracts had matured. One sees not only a shift in colors from blues and greens to yellows and browns, but also less distinct forms on the bottom painting, no doubt due to the scattering of light caused by his cataracts. This is an optical effect that neural processes previously described cannot compensate.

Although the onset of his visual loss was gradual, he seems not to have remarked about it until about 1908, at age 68. Four years later, a Paris doctor confirmed the diagnosis of bilateral cataracts made by Monet’s country physician. As his cataracts became worse, he found it impossible to paint in bright light or to depict scenes with bright backgrounds — again, to be sure, due to the scattering of light and the concomitant degradation of the retinal image.

Despite his poor vision, Monet pursued his dream of many years to create vast canvases that
Fig. 1.25: **Top**: Claude Monet (1871) *Boats on the Thames, London.* Oil on canvas, 47 × 72 cm. Private Collection, Monte Carlo.

**Bottom**: Claude Monet (1904) *Houses of Parliament (Rays of Sun in the Fog).* Oil on canvas, 81 × 92 cm. Musée d'Orsay, Paris.
Fig. 1.26: Top: Claude Monet (1899) *Le bassin aux nymphéas* [Waterlilies and Japanese Bridge.] Oil on canvas, 91 × 90 cm. The Art Museum, Princeton University. From the Collection of William Church Osborn, Trustee of Princeton University (1914–1951), President of the Metropolitan Museum of Art (1941–1947); given by his family. (Photo credit: Clerl Fiori.)

would surround the entire interior of a room, depicting water and plants in a manner that revealed the elusive brilliance of nature. He pursued the project with vigor and even built a large new studio to accommodate his large-scale canvases. Monet called this project a bit of a folly and referred to the paintings as his "Grandes Décorations." At this point he refused cataract surgery, fearing it would make his vision even worse. Yet he could no longer discriminate between many of his paints, relying instead on reading the labels for selecting his colors and then remembering their precise arrangement on his palette. He realized that many of his pictures were quite dark; and on several occasions, after comparing these canvases with his earlier works, he slashed and destroyed them.

During these years, Monet received frequent visits from his long-time friend, Georges Clemenceau, a remarkable man who had ascended to the rank of Premier of France. By the beginning of 1917, the end of the first World War was in sight, and Monet had agreed to donate two large panels of his "Grandes Décorations" to France to celebrate the armistice. Clemenceau, however, convinced him to donate not two panels but all 12 that Monet had planned with the stipulation that a building would be constructed to house them in the manner that Monet had envisioned. The number was later increased to 19 panels in order to accommodate the architect's plan to house them in the Orangerie des Tuileries in Paris. There was, of course, some question in Monet's mind about whether he would have the energy and the eyesight needed to complete this enormous undertaking.

Monet had once said that he wished he had been born blind and then suddenly made to see so that he could paint his impressions without the bias of prior experience. Soon, a version of his wish would be granted. By 1922, at the age of 82, he had become essentially blind in the right eye and had only a little useful vision in the left eye, according to his medical records. Determined to continue, he said that "I will paint almost blind as Beethoven composed completely deaf" (Stuckey, 1995, p. 251). To improve his vision for a few hours at a time, he used a prescribed mydriatic to dilate his pupils (Ravin, 1985). Monet used very little blue in his paintings at this time, presumably because his dense cataracts would have transmitted so little short-wave light that blue would have been indistinguishable from black. The compensation processes described above may have reached the physiological limit so that by the summer of 1922 he found it necessary to stop painting. Clemenceau finally convinced Monet to go ahead with cataract surgery in his right eye that year.

Within six months of cataract extraction, Monet developed a secondary cataract, an opacification of the posterior capsule of the operated eye. This is a common complication of cataract surgery; and, although it did not surprise his physician, the opacity was a traumatic development for Monet. In July 1923 the cloudy membrane was extracted in Monet's home in Giverny. Monet was prescribed glasses, but they caused him to experience double vision and optical distortion. He discovered that his vision improved if he covered one eye, usually the left. Now Monet complained that through his left eye, with a remaining cataract, everything was too yellow, while through the eye with the cataract removed (aphakic eye), he experienced everything as too blue. Figure 1.27 shows his paintings of his House Seen from the Rose Garden which are believed to be painted with only one eye or the other (Lanthony, 1993). The difference between the views through the different eyes is striking.

One might wonder why the difference in yellow filters in Monet's eyes should so strikingly affect his choice of colors. After all, in the aphakic eye, Monet's retina should receive more short-wave-length light reflected not only from the scene he is trying to depict but equally from the blue paints on his palette. The net effect would therefore seem to require the same match between the scene and the canvas with or without a dense yellow cataract. From this point of view, the yellow filter should have no effect on Monet's paintings because it lies in front of both the original scene and his palette.

This analysis would be correct if our visual system were capable of responding to each wavelength of light separately and if there were enough pigments to match each wavelength. However, neither of these two requirements is met. As Clemenceau put it to Monet, "The steel of your eyesight breaks the crust of appearances, and you..."
Fig. 1.27: **Top:** Claude Monet (1925) *La maison vue du jardin aux roses.* [*House Seen from the Rose Garden.*] Oil on canvas, 81 × 92 cm. Musée Marmottan, Paris.

**Bottom:** Claude Monet (1925) *La maison vue du jardin aux roses.* [*House Seen from the Rose Garden.*] Oil on canvas, 89 × 100 cm. Musée Marmottan, Paris.
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penetrate the inner substance of things in order to decompose it into projectors of light which you re-compose with the brush so that you may re-establish subtly upon our retinas the effect of sensations in their fullest intensity” (Clemenceau, 1930, pp. 18–19). Expressed less poetically, the painter does not make a physical match between the original scene and the canvas but a visual (approximately metameric) match. These matches depend on the shapes of the receptor action spectra (Fig. 1.6), and the latter are modified (as specified at the cornea) by age-related changes in the lens (Wright, 1928–29). In short, the senescent or cataractous lens modifies the receptor sensitivities in two ways: First, it alters the shapes of the receptor action spectra (specified at the cornea) by reducing sensitivity more at short wavelengths than at middle and long wavelengths. Second, it reduces the relative heights of the action spectra, affecting S-cones more than M- or L-cones. Processes such as color matching which depend on the shapes of the photoreceptor action spectra cannot be compensated neurally because each cone type obeys the principle of univariance (i.e., all absorbed quanta produce the same response in a photoreceptor), while relative sensitivities or heights of the curves can be compensated to a large extent. The net effect is that lenticular senescence affects color matches more than color appearance (Werner, 1996).

Following cataract surgery, patients often report a resurgence of blue experienced through the operated eye, as would be expected due to the removal of their dense yellow lens, but they adapt rather quickly over the course of weeks or months. Monet did not adapt so quickly, but some of his difficulty may have been with his impatience, which led his physician frequently to change the prescribed colored lenses that were intended to equate color appearance in the two eyes (Ravin, 1985). This process commenced when a Paris ophthalmologist, Jacques Mawas, prescribed a pair of glasses that were tinted yellowish-green. This eliminated Monet’s previous complaint that he sees nothing but blue. Up to that point, he relied on his left eye for painting, but now switched to his right eye. Monet and Dr. Mawas tried glasses with various tints during the next two years. In the end, they settled on a pair of untinted glasses that Monet described as quite satisfactory. No doubt this outcome was due to chromatic adaptation in his visual system over this period.

In July 1925, three years after his original cataract extraction, Monet declared that his color vision was completely restored and his mood was ebullient. Now 85 years old, he resumed his work and completed not the 19 promised canvases for his “Grandes Décorations” but 22.

Monet never saw these canvases displayed in the room that he had envisioned. He died on 5 December 1926. Next to his bed was a book opened to Baudelaire’s poem, “The Stranger” (Vidal, 1956). It goes, “Tell me, enigmatical man, whom do you love best, your father, your mother, your sister, or your brother?” To which the man replied, “I love the clouds.” It was fitting that Clemenceau was by his side and was the one to close his eyes. Monet once said to Clemenceau, “Put your hand in mine and let us help one another to see things better” (Tucker, 1995, p. 225). Two months after closing Monet’s eyes, Clemenceau helped the world to see better through Monet by opening the Orangerie des Tuileries with his “Grandes Décorations.”

1.11  Summary

The life span of the Impressionist Claude Monet, 1840 to 1926, encompassed some of the most important developments in how color is now understood in art and science. In his paintings, Monet made the ephemeral effects of light and color his central subject matter. He is likely to have been influenced by J. W. v. Goethe via J. M. W. Turner and M. E. Chevreul via E. Delacroix, who exploited new ideas about additive color mixture and simultaneous contrast. Paintings from this period provide useful illustrations of the discoveries and theories of Monet’s contemporaries in science, including J. C. Maxwell, H. v. Helmholtz, E. Hering and J. v. Kries, although he was probably not directly influenced by them. Their scientific theories are cornerstones for current thinking about color vision and provide a useful framework for analyzing age-related changes in color perception.
Monet's vision changed during his life, perhaps due in part to accelerated aging caused by sunlight to which he was often exposed by virtue of his painting *en plein air*. Light, especially UV light, may accelerate the normal age-related changes in the lens and photoreceptors. The cone pathways lose sensitivity on a continuous basis from early adulthood to old age. When expressed in terms of sensitivity at the cornea, S-, M- and L-cones appear to lose sensitivity at approximately the same rate with age. This is somewhat surprising because senescent changes in the lens produce a selective loss in the amount of short wavelength light that can reach the retina, a reduction commonly thought to reduce sensitivity of the visual system to blue hues. Monet's reaction to his own senescent lens, culminating in a cataract, has been taken to support this view. Recent studies, however, show that the visual system adapts to normal lenticular senescence and actively rebalances the sensitivity of color mechanisms to support constancy of color perception across the life span.

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