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 × 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.
Act 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 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 can be quite misleading. A closer look at the visual system shows that it is constantly changing throughout life (Weale, 1982; Werner et al., 1990).
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Fig. 1.3: Schematic cross-section of the human eye with the retina shown in an enlarged view. The ocular media include the cornea, aqueous contained in the anterior chamber, lens and vitreous humor. The retina, shown in a magnified view, includes five principal cell types, photoreceptors (rods and cones), horizontal cells, bipolars, amacrine and ganglion cells (the axons of which form the optic nerve).

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 cataracts: (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 non-human 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 fundoscopically 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 ≥10 °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 phototoxic insult associated with sunlight. For example, distributed throughout the eye are various antioxidant molecules (e.g., superoxide dismutase, α-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 carotenoid 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 piece-meal 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.
1.3 The Trivariance of Color Mixture: Maxwell and Helmholtz

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 quanta 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 resultant 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 mostly 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 explicable 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-
Fig. 1.6: Relative log quantal sensitivity of the three classes of human cone photoreceptors. 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).

...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 Stavle (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-

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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 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.](image)