hues needed to describe the stimuli. Similarly, when asked to describe the percentage of chromatic and achromatic components of spectral lights (Kraft and Werner, 1997), and when asked to find a mixture of unique blue and yellow that appeared white (Werner and Schefrin, 1993), young and old did not differ significantly.

These results demonstrate a surprising degree of stability in color perception across the life span, even though age-related changes in the lens alter the spectral distribution of light reaching the retina. This would seem to be possible only if the visual system compensates for or adapts to those changes in retinal illumination that occur with lenticular senescence. Clear evidence for this compensation was found in a study by Kraft and Werner (1994) of the brightness of monochromatic lights for 50 observers ranging in age from 19 to 85 years. Each monochromatic light (420–700 nm; 16 wavelengths) was matched in brightness to a white standard. In the same individuals, the density of the ocular media was estimated so that brightness sensitivity could be specified at the retina, as shown in Figure 1.19 (white squares). On average, brightness sensitivity at middle and long-wavelengths does not change significantly, but at short wavelengths it actually increases with age. This increase occurs only at the retina, and under natural conditions it is not enough to eliminate some brightness loss (at the cornea) for violet lights in the elderly. However, across 6 decades it implies a doubling of brightness sensitivity, which goes a long way toward restoring constancy that would otherwise be disrupted by the yellowing of the lens.

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 Grande 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, 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-
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.

In the visual field, 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
Fig. 1.23: **Top:** Claude Monet (1891) *Meules, Effet de Gelee Blanche.* [Hay Stacks. Snow Effect. Sunshine.] Oil on canvas 65 × 92 cm. National Gallery of Scotland, Edinburgh.

**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.
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'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).

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.
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) *Bateaux dans le Bassin de Londres.* (Boats on the Thames, London.) Oil on canvas, 47 × 72 cm. Private Collection, Monte Carlo.  
**Bottom:** Claude Monet (1904) *Londres, le Parlement, Trouée de soleil dans le brouillard.* (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.* [*Water-lilies and Japanese Bridge.*] Oil on canvas, 91 x 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: Clem 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-wavelength 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.
of color perception.

The age-related changes in color perception vision and learning are isolated phenomena, not
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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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