The Retinex Theory of Color Vision

A retina-and-cortex system (retinex) may treat a color as a code for a three-part report from the retina, independent of the flux of radiant energy but correlated with the reflectance of objects.

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Edwin H. Land
December, 1977

The scientific tradition of simplifying the conditions of an experiment has left us until recently without a satisfactory explanation of how the eye sees color in everyday life. Paradoxically the modern technology of color photography has reinforced the belief that the colors discerned by Newton in the spectrum are, with minor qualifications, the colors of the world around us. We know, for example, that if we use daylight color film when we take a picture in the light shed by an ordinary tungsten-filament lamp, the picture will turn out to have a strong reddish cast. That, we say, is because the rays from the tungsten filament are too "red," never asking how we ourselves can move constantly in and out of tungsten-lit worlds without experiencing any change in the color of familiar objects: apples, lemons, strawberries, bread, human faces (the tones of which are so hard to get right on a television screen).

How, then, does the eye deal with the excess of "red" in a tungsten-lit room? As I hope to demonstrate in this chapter, the eye, in determining color, never perceives the extra red because it does not depend on the flux of radiant energy reaching it. The eye has evolved to see the world in unchanging colors, regardless of always unpredictable, shifting and uneven illumination. How the eye achieves this remarkable feat has fascinated me for many years.

In 1959 I described in an article for SCIENTIFIC AMERICAN, a series of experiments in which a scene created by the superposition of two black-and-white transparencies, one projected through a red filter and the other projected without a filter (that is, in white light), conveys to the eye nearly the gamut of colors present in the original scene [see "Experiments in Color Vision," by Edwin H. Land; SCIENTIFIC AMERICAN, May 1959]. To produce such "red-and-white" images the picture projected through the red filter is taken through a red filter and the picture projected in white light is taken through a green filter. It would be expected that the superposed image on the projection screen could generate only red, white and various shades of pink. Actually one sees a picture remarkably similar to the full-color photograph reproduced in Figure 3.1. (Black and white images of the same still life taken with four different film-filter combinations are shown in Figure 3.2.) In the red-and-white photographic projection peppers are green, radishes and strawberries are red, the orange is orange, the lemon and ba-

Figure 3.1 STILL LIFE was used to make the four black-and-white images presented in Figure 3.2. The reproduction of the still life was made by conventional processes of color photography and photoengraving to show the reader what the colors of the original objects in the scene were. The black-and-white images were made with film-filter combinations that closely duplicate the separate wavelength sensitivities of the four systems of photoreceptors in the retina of the eye: the three systems of cone cells and the hypersensitive system of rod cells.
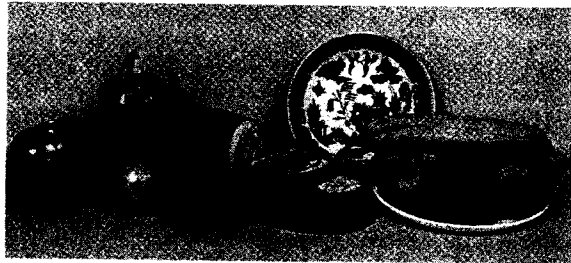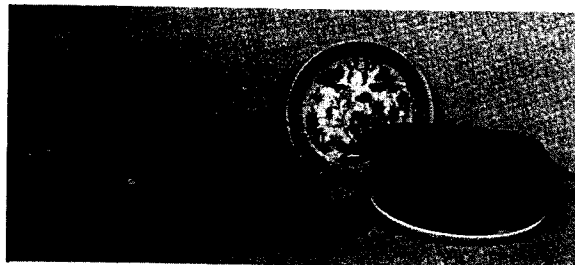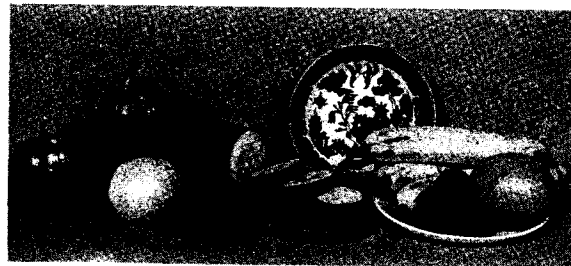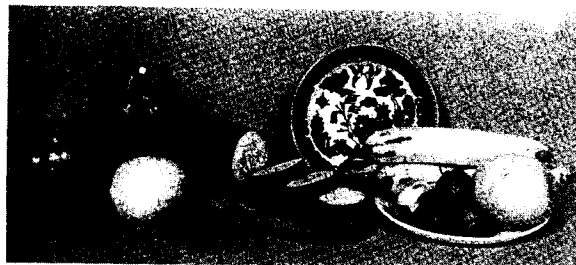
Figure 3.2 BLACK-AND-WHITE IMAGES OF STILL LIFE taken with four different film-filter combinations create retinex records. Film whose spectral response was altered to match the spectral sensitivity of the long-wave cone pigments in the eye produces a colorless image that approximates the image produced by the long-wave cones by themselves (top left). The same scene is produced as it would be viewed by the middle-wave cone pigment (top right), by the short-wave cone pigment (bottom left) and by the rods (bottom right). Unlike cone images, images produced by the rod pigment can be studied in isolation at very low light levels, without interference from the much less sensitive cone systems.

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The challenge presented by our early red-and-white experiments led us step by step over a 20-year period to an explanation of how the visual system is able to extract reliable color information from the world around us, a world in which virtually every scene is lighted unevenly, in which the spectral composition of the radiation falling on a scene can vary enormously and in which illumination as brief as a lightning flash suffices for the accurate identification of color. If the nature of the responses of the photoreceptors in the retina of the eye even approximated what most of us were taught in school, functioning primarily as intensity-level meters with peaks in three different parts of the spectrum, we would be continually confusing one color with another. An object that looked yellow in one part of our field of view might look green or gray or even red when moved to a different part of the field. The fact remains that objects retain their color identity under a great variety of lighting conditions. This constancy is not a minor second-order effect but is so fundamental as to call for a new description of how we see color.

The visual pigments are photosensitive molecules that respond to a wide band of light frequencies. The three pigments in the cone cells of the retina cover the visible spectrum in three broad, overlapping curves. The pigment with a peak sensitivity at a wavelength of 440 nanometers responds in some degree to the entire lower-frequency half of the visible spectrum. Each of the other two pigments responds to almost two-thirds of the visible spectrum, the two being offset at their peaks by barely 30 nanometers, with their peak sensitivities located at 535 and 565 nanometers (see Figure 3.3).

In this discussion the names of colors—"red," "green," "blue" and so on—will be reserved for the color sensation we have when we look at the world around us. In short, only our eyes can categorize the color of objects: spectrophotometers cannot. This point is not a trivial one because many people viewing some of our experiments for the first time will identify something as being red or green but will then ask, as if their eyes were being fooled, "What color is it really?" The answer is that the eye is not being fooled. It is functioning exactly as it must with involuntary reliability to see constant colors in a world illuminated by shifting and unpredictable fluxes of radiant energy.
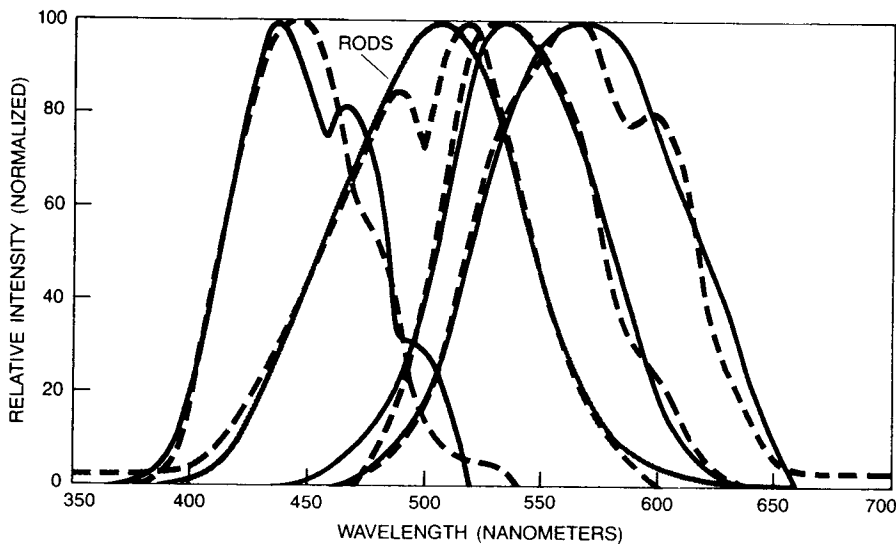
Figure 3.3 NORMALIZED SPECTRAL SENSITIVITIES OF FOUR VISUAL PIGMENTS (*solid lines*) span the visual spectrum in overlapping curves. Curve that peaks at about 500 nanometers corresponds to sensitivity of rod pigment. Other three curves represent cone pigments. Broken lines show sensitivities of the film-filter combinations that were selected to match the sensitivities of the four retinal pigments and used to make the black-and-white retinex records in Figure 3.2. Cone curves are adapted from work of Paul Brown and George Wald of Harvard University. The rod curve is standard scotopic luminosity curve.
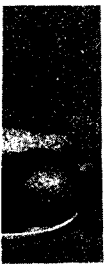
Since I believe the study of color in fully colored images is best begun by examining images that are completely devoid of and completely uncomplicated by the experience of color, let me describe that experience in some detail. The hypersensitive system based on the rod cells in the retina functions at light levels as much as 1,000 times weaker than the systems based on the cone cells do, so that it is possible to answer the interesting question: What colors will one see if only the rod system is activated? One procedure is to put on a pair of tightly fitting goggles equipped with neutral-density filters that reduce the incident light by a factor of 30,000. After one has worn the goggles for about half an hour objects in a room illuminated to the typical level of 20 foot-candles will become visible. The effective illumination in the room will thus be 1/1,500 foot-candle. As one looks around the room the familiar colored objects will be seen devoid of color, exhibiting instead a range of lightnesses from white to black, much as they would appear in a black-and-white photograph taken through a green color-separation filter. In other words, the reds will appear very dark, the greens lighter, the blues dark, the whites light and the blacks very dark.

In this colorless world one finds that the nature of the image is not determined by the flux of radiant energy reaching the eye. The illumination can easily be arranged so that there is more flux from a region that continues to look very dark than there is from a region that continues to look very light, whether these regions are three-dimensional objects or artifacts contrived with a montage of dark and light pieces of paper. The paradox immediately arises that each of the objects, the pieces of paper for example, whether dark or light or in between, maintains its lightness without significant change as it is moved around the room into regions of higher or lower flux. Light papers will be seen as being light and dark papers simultaneously as being dark, even with the same flux coming from each of them to the eye. Strong gradients of flux across the field will be apparent only weakly, if at all.

Furthermore, in an intricate collage of areas of various lightnesses, sizes and shapes, the lightness of a given element does not change visibly as it is relocated in any part of the collage and associated with a new arbitrary surround. When a small area is totally surrounded by a large area, the lightness of the small area will change somewhat depending on whether the large area is darker or lighter than the small one. In general, however, the impressive fact

is that the lightness of a given area is not appreciably modified by the immediately surrounding areas, nor is it modified by the still larger areas surrounding them.

Although I have been describing a colorless world as it is seen by the hypersensitive receptors of rod vision, all the observations about the stability of lightness values can readily be reproduced with a montage of white, black and gray papers viewed at ordinary light levels. If, for example, a square of matte-surface black paper or, better still, black velvet is placed at one side of such a montage and a square of white paper is placed at the opposite side several feet away, with an assortment of light and dark papers scattered in between, one can place a strong light source close enough to the black square so that it sends more radiant energy to the eye than the white square, remote from the light; yet the black square will continue to look black and the white square white. In fact, with the montage still strongly illuminated from one side either the black square or the white one can be moved to any other part of the montage without a significant change in its appearance.

This remarkable ability of the eye to discover lightness values independent of flux, so convincingly demonstrated when only a single photoreceptor system is operating, is the rock on which a satisfactory description of color vision can be built. The first response of the visual system is for the receptors to absorb the light falling on the retina. Whereas the initial signal produced in the outer segment of the receptor cell is apparently proportional to the light flux absorbed by the visual pigment, the final comprehensive response of the visual system is "lightness," which shows little or no relation to the light flux absorbed by the visual pigment.

The processing of fluxes to generate lightnesses could occur in the retina, or in the cerebral cortex, or partially in both. Since we are uncertain of the location of the mechanisms that mediate these processes, I have coined the term retinex (a combination of retina and cortex) to describe the ensemble of biological mechanisms that convert flux into a pattern of lightnesses. I shall therefore use the term throughout this chapter in referring to these biological mechanisms. I shall also reserve the term lightness to mean the sensation produced by a biological system. Although the rods can be stimulated at light intensities below the cone threshold, the cones can-

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not be stimulated without exciting the rods. For cones we must study the lightness images produced by each individual set of receptors using retinex photography, as I shall explain below, or learn the properties of lightness images from model calculations based on spectroradiometric measurements.

Now that we know that at low light levels an isolated receptor system generates an image in terms of lightness that is completely free of color, might it be possible to bring one of the cone systems into operation along with the hypersensitive system, so that only the completely colorless system and one other were functioning? This two-receptor experiment has been carried out and provides a powerful confirmation of the ideas derived from all our binary work with red-and-white images and subsequent ternary studies with multicolored displays seen under various illuminants. The experiment, rapidly becoming a classic, was devised by my colleagues John J. McCann and Jeanne L. Benton.

McCann and Benton illuminated a color display with a narrow wave band of light at 550 nanometers. The light level was raised just above the amount needed to make the display visible to the

dark-adapted eye, thus ensuring that only the hypersensitive system was operating. They then added a second narrow-band illuminant at 656 nanometers, with its level adjusted so that it was just sufficient to activate the long-wave receptor system but not the middle-wave system. Under these conditions only two receptor systems, namely the rods and the long-wave cones, were receiving enough light to function (see Figure 3.4).

The resulting image exhibited a remarkable range of color, enabling an observer to assign to each area in the display the same color name it would have if it were illuminated above the cone threshold. The result is reminiscent of the multicolored images produced by the red-and-white system. The demonstration explicitly confirms our early proposition that the lightness information collected at two wave bands by separate receptor systems is not averaged, point by point and area by area, but is kept distinct and is compared. We know that the rod system does not produce a colored image when the image is seen by itself, and we know that the long-wave light alone cannot produce an image with a variety of colors. The combination, however, gives rise to a wide variety of colors, namely reds, yellows, browns, blue-greens, grays and blacks.
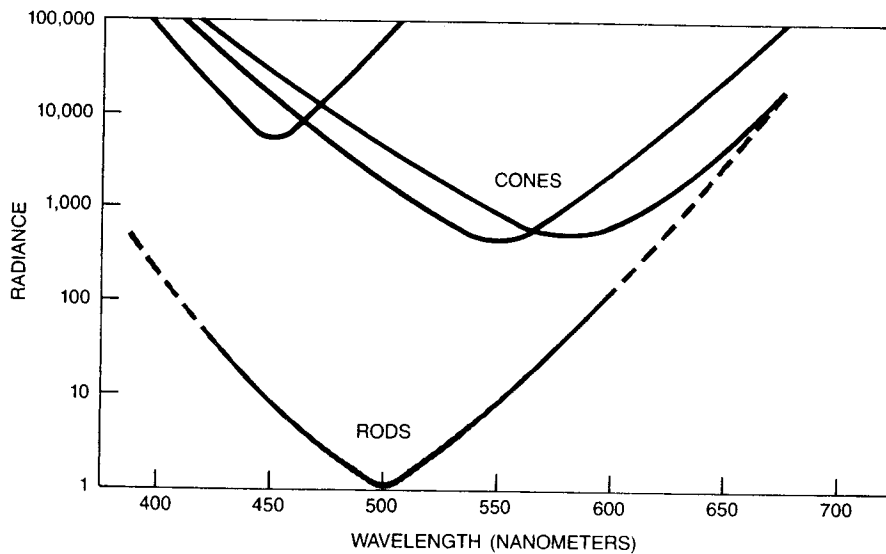
Figure 3.4 THRESHOLD RESPONSES OF RETINAL RECEPTORS vary by large factors. The hypersensitive rod system provides vision at radiance levels about 1,000 times weaker than the light levels needed to activate the cone systems. It has been shown in author's laboratory that multicolored scenes exhibit nearly their normal range of colors when they are viewed at light levels so adjusted that only rod system and one cone system, the long-wave system, are responding.

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What, then, accounts for the color? The emergence of variegated colors can be ascribed to a process operating somewhere along the visual pathway that compares the lightnesses of the separate images on two wave bands, provided by the two independent retinex systems. The two-receptor experiment makes it plausible that when three independent images constituting the lightnesses of the short-, middle- and long-wave sets of receptors are associated to give a full-colored image, it is the comparison of the respective lightnesses, region by region, that determines the color of each region. The reason the color at any point in an image is essentially independent of the ratio of the three fluxes on three wave bands is that color depends only on the lightness in each wave band and lightness is independent of flux.

As we have seen, the spectral sensitivities of the visual pigments overlap broadly. If we illuminated a scene with the entire range of wavelengths to which a single visual pigment is sensitive, we would see a large variety of colors because more than one retinex system would respond. With the help of filters and appropriate film emulsions, however, we can isolate the lightnesses that would ordinarily be incorporated into the sensation of color. We call black-and-white photographs made for this purpose retinex records.

The photographic technique, making use of silver emulsions, performs two functions. First, the system provides spectral sensitivities that are the same as those of the visual pigments. Second, it generates black-and-white pictures for a human observer to examine. It is the human visual system that converts the photographic pattern deposited in silver into lightness. Ideally we should like our observer to examine the black-and-white pattern with only one set of cones, reporting the lightnesses appropriate to that set. At any point in the black-and-white pattern, however, the reflectance is essentially the same throughout the visible spectrum. Therefore with a black-and-white photograph we stimulate all the receptors with the same information, that is, with the energies that would be absorbed by a single visual pigment. If we assume that all the retinex systems process information in an identical manner, we can propose that sending this identical information to several sets of receptors is the same as sending it to only one receptor, thereby enabling us to see what the image would look like if it were possible to isolate it.

In Figure 3.2, the reader will see three black-and-white pictures taken through retinex filters that simulate the response of the three cone pigments. The strawberries and radishes, for example, are light on the long-wave record, darker on the middle-wave record and darkest on the short-wave record. Although the orange and lemon are about as dark as the strawberries and radishes on the short-wave record, they are nearly as light on the middle-wave record as they are on the long-wave record. On the printed page the distinctions are subtle. To the eye viewing an actual full-color scene the subtle distinctions provide all the information needed to distinguish countless shades and tints of every color.

After the three lightnesses of an area have been determined by the three retinex systems no further information is necessary to characterize the color of any object in the field of view. Any specific color is a report on a trio of three specific lightnesses. For each trio of lightnesses there is a specific and unique color.

The limitations of color photography make it impossible to show the reader the demonstrations readily accomplished in our laboratory, which dramatically reveal the independence of perceived color from the flux reaching the eye. What the reader would see would be two boards four and a half feet square identically covered with about 100 pieces of paper of various colors and shapes. In order to minimize the role of specular reflectance the papers have matte surfaces and, except for black, have a minimum reflectance of at least 10 percent for any part of the visible spectrum. In these displays, which we call "color Mondrians" (after the Dutch painter to whose work they bear a certain resemblance), the papers are arranged so that each one is surrounded by at least five or six others of different colors (see Figure 3.5).

Each of the identical Mondrians is illuminated by its own set of three projectors equipped with sharply cutting band-pass filters (not retinex filters): one at 670 nanometers embracing a band of long waves, one at 540 nanometers embracing a band of middle waves and one at 450 nanometers embracing a band of short waves. The amount of light from each illuminating projector is controlled by a separate variable transformer. In addition the illuminating projectors have synchronized solenoid-activated shutters to control the duration of illumination. There is a telescopic photometer that can be precisely aimed at any region of either Mondrian to

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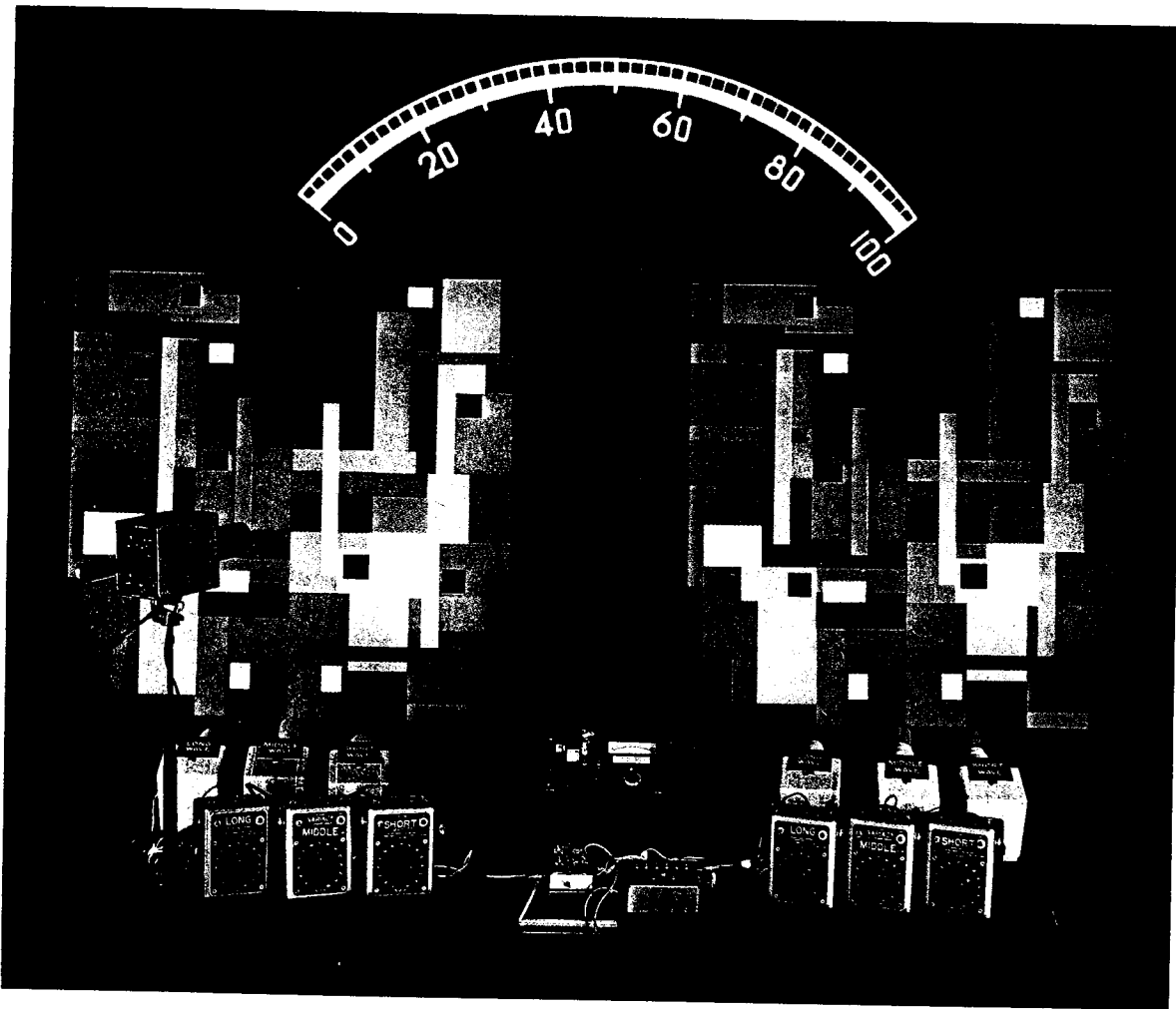l-activated
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Figure 3.5 "COLOR MONDRIAN' EXPERIMENT employs two identical displays of sheets of colored paper with a matte finish mounted on boards. Each "Mondrian" is illuminated with its own set of three projector illuminators equipped with band-pass filters and independent brightness controls. A telescopic photometer can be pointed at any area to measure the flux, one wave band at a time. In a typical experiment the illuminators can be adjusted so that the white area in the Mondrian at the left and the green area (or some other area) in the Mondrian at the right are both sending the same triplet of radiant energies to the eye. Under actual viewing conditions, white area continues to look white and green area continues to look green even though the eye is receiving the same flux triplet from both areas.

measure the amount of radiation reflected from any point and therefore the amount of flux reaching the eye. The output of the photometer is projected on a scale above the Mondrian, where it can be seen by those taking part in the demonstration.

The demonstration begins with the three illuminating projectors turned on the Mondrian on the left; the Mondrian on the right remains dark. The variable transformers are set so that the entire array of papers in the left Mondrian are deeply colored and at the same time the whites are good whites. This setting is not critical. Then, using one projector at a time and hence only one wave band at a time, we measure with the telescopic photometer the energy reaching the eye from some particular area, say a white rectangle. The readings from the white area

(in milliwatts per steradian per square meter) are 65 units of long-wave light, 30 units of middle-wave light and five units of short-wave light. We have now established the three energies associated with that sensation of white.

We turn off the three projectors illuminating the color Mondrian on the left. On the right we turn on only the long-wave projector. We select a different area of unknown color and adjust the long-wave light until the long-wave energy coming to the eye from the selected area is the same as the long-wave energy that a moment ago came from the white paper in the Mondrian on the left, 65 units. We turn off the long-wave projector and separately adjust the transformers controlling the middle- and short-wave projectors, one after the other, so that the energies sent to the eye from the selected area are also the same as those that came from the white area on the left. We have not yet turned on all three light sources simultaneously, but we know that when we do so, the triplet of energies reaching the eye from the selected area of still unknown color will be identical with the triplet that had previously produced the sensation white.

When we turn on the three illuminants, we discover that the area in the Mondrian on the right is green. We now illuminate the Mondrian on the left with its illuminants at their original settings so that both Mondrians can be viewed simultaneously. The white area on the left continues to look white and

the green area on the right continues to look green, yet both are sending to the eye the same triplet of energies: 65, 30 and five in the chosen units (see Figure 3.6).

We turn off the illuminants for both Mondrians and select some other area in the left Mondrian and sequentially adjust the energies reaching the eye from it so that they are the same as the energies that originally gave rise to the sensation of white and also gave rise to the sensation of green in the right Mondrian. When we turn on all three projectors illuminating the left Mondrian, we see that this time the selected area is yellow. The triplet of energies reaching our eye is the same one that had previously produced the sensations of white and green. Again, if we wish, the yellow and green can be viewed simultaneously, with yellow on the left and green on the right.

We can continue the demonstration with other areas such as blue, gray, red and so on. It is dramatically demonstrated that the sensation of color is not related to the product of reflectance times illumination, namely energy, although that product appears to be the only information reaching the eye from the various areas in the Mondrians.

In order to demonstrate that the color sensations in these experiments do not involve extensive chromatic adaptation of retinal pigments the projectors are equipped with synchronized shutters so that the Mondrians can be viewed in a brief flash, a tenth of

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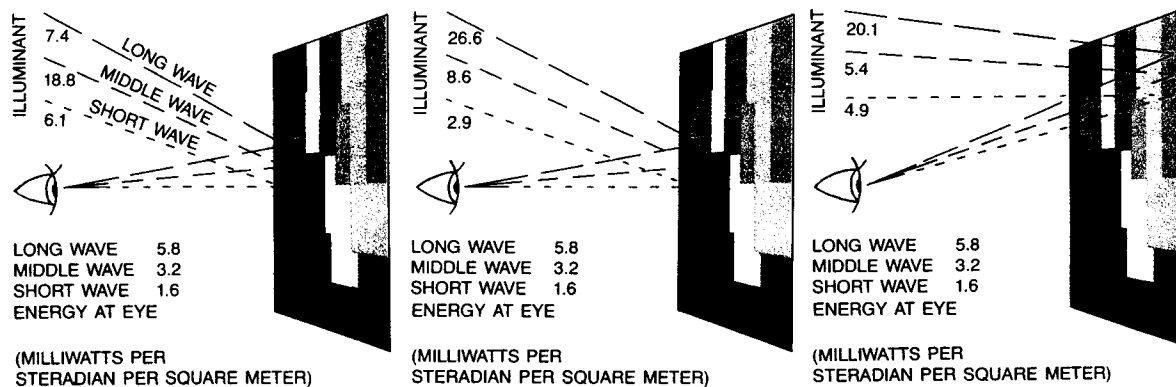
Figure 3.6 IDENTICAL ENERGY FLUXES AT THE EYE provide different color sensations in the Mondrian experiments. In this example, with the illuminants from the long-wave, middle-wave and short-wave illuminators adjusted as indicated, an area that looks red continues to look red (*left*), an area that looks blue continues to look blue (*middle*) and an area that looks green continues to look green (*right*), even though all three are sending to the eye the same triplet of long-, middle- and short-wave energies. The same triplet can be made to come from any other area: if the area is white, it remains white; if the area is gray, it remains gray; if it is yellow, it remains yellow, and so on.

a second or less in duration. Regardless of the brevity of observation the results of the demonstrations are not altered. Thus one can say that neither chromatic adaptation nor eye motion is involved in producing the observed colors. Finally, the very essence of the design of the color Mondrian is to obviate the significance of the shape and size of surrounding areas, of the familiarity of objects and of the memory of color. Curiously, from time to time there is a casual attempt to adduce what is called color constancy as an explanation of these demonstrations. Clearly color constancy is only a compact designation of the remarkable competence that is the subject of this article.

The mystery is how we can all agree with precision on the colors we see when there is no obvious physical quantity at a point that will enable us to specify the color or an object. Indeed, one can say the stimulus for the color of a point in an area is not the radiation from that point. The task of psychophysics is to find the nature of the stimulus for that color.

Here let us remember that what the eye does unfailingly well is to discover lightness values independent of flux. We say this to be true for a single receptor system, the rod system, operating alone and for the three cone systems operating collectively when they viewed an array of white, gray and black papers. Let us now illuminate the colored Mondrian array with light from just one of the three projectors, say the projector supplying long-wave light, and observe the effect of increasing and decreasing the flux by a large factor. We observe that the various areas maintain a constant rank order of lightness. If, however, we switch the illumination to a different wave band, say the middle wave band, the lightnesses of many of the areas will change; many of the 100 or so areas will occupy a different rank order from lightest to darkest. Under the short-wave-band illuminant there will be yet a third rank order. Specifically, a red paper will be seen as being light in the long-wave light, darker in middle-wave light and very dark in short-wave light. A blue paper, on the other hand, will be light in short-wave light and very dark in both middle- and long-wave light. Papers of other colors will exhibit different triplets of lightnesses. When we conducted such experiments nearly 20 years ago, we were led inevitably to the conclusion that the triplets of lightnesses, area by area, provided the set of constancies we needed to serve as the stimuli for color, independent of flux.

It is evident that the lightnesses exhibited by a given piece of colored paper under illuminants of three different wave bands is related to the amount of energy the paper reflects to the eye at different wavelengths. Let us now examine, by means of a particular experiment, how such reflectances can be related step by step to perceived lightnesses and how, in the process, the radiant flux that reaches the eye — the ultimate source of knowledge about lightness — finally becomes irrelevant to the sensation of color.

In our laboratory McCann, Suzanne P. McKee and Thomas H. Taylor made a systematic study of observers' responses to a simplified color Mondrian with areas of 17 different colors. They asked the observers to match the 17 areas one at a time under different illuminants with colored squares of paper that had been selected from a standard color-reference book, *The Munsell Book of Color,* and that were viewed under a constant "white" illumination.

The illuminants on the Mondrian were adjusted in five separate matching experiments so that five different areas (gray, red, yellow, blue and green) sent to the eye an identical triplet of radiances. The observer began by selecting a matching Munsell "chip" for each of the 17 areas in the Mondrian when the gray area in the Mondrian sent a particular triplet of energies to the eye. Another set of 17 matching Munsell chips was selected when the same triplet was later sent to the eye by a red area in the Mondrian, and the same was done for yellow, blue and green areas under illuminants that supplied the same triplet of energies.

Figures 3.7, 3.8, 3.9 and 3.10 show the details of the experiment and the five different Munsell colors the observers selected to match the five areas when each area sent to the eye precisely the same triplet of energies. In spite of the constancy of the energy reaching one eye from the Mondrian, each observer, using the other eye, selected Munsell chips that were gray, red, yellow, blue and green.

The constant illumination used in viewing the Munsell book was a triplet of illuminants at three wavelengths that observers judged to produce the "best" white. The actual triplet of wavelengths reaching the eye from the whitest paper in the Munsell book was 11.5 units of long-wave light, 7.8 units of middle-wave light and 3.3 units of short-wave light. The illuminants supplied energy in narrow bands with peaks at 630 nanometers, 530 nanometers and 450 nanometers. A similar triplet of
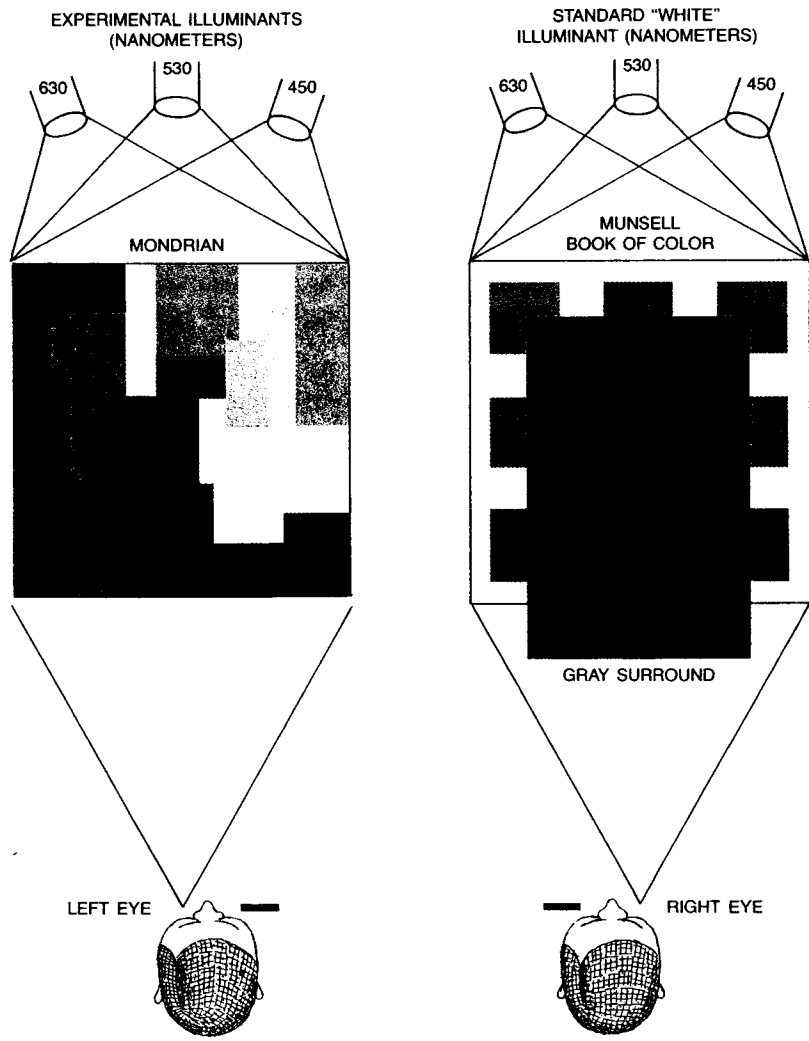
EXPERIMENTAL ILLUMINANTS
(NANOMETERS)

STANDARD "WHITE"
ILLUMINANT (NANOMETERS)

Figure 3.7 COLOR-MATCHING EXPERIMENT uses a simplified Mondrian (*left*) and standard color reference "chips" (*right*). The Mondrian is illuminated with three narrow-band light sources (see text), the ratio of which is such that the energies reflected to the eye from any area equals those that previously reached the eye from some other area. In this experiment different color areas were selected in sequence to send the same energies to the eye, and for each one the observer selected the chip that came closest to matching it. The chips were illuminated with a constant spectral mixture of three narrow-band lights so that the white chip appeared the "best white." One eye was used for viewing the Mondrian and the other for viewing chips. The chip was always surrounded by the same gray paper.

Figure 3.8 I
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narrow-band illuminants were mixed in various proportions to illuminate the Mondrian.

At this point the reader might ask: Would not a single gray area exhibit a pronounced change in color if the surrounding papers had reflected light of widely differing spectral composition? Could these changes in color account for the results of the Mon-

drian experiments? The answer to the questions is that no manipulation of surrounding papers in the Mondrian is capable of making the gray paper match the red, yellow, blue, and green Munsell papers selected by the observers in the Mondrian experiment.

McCann, John A. Hall and I have examined the

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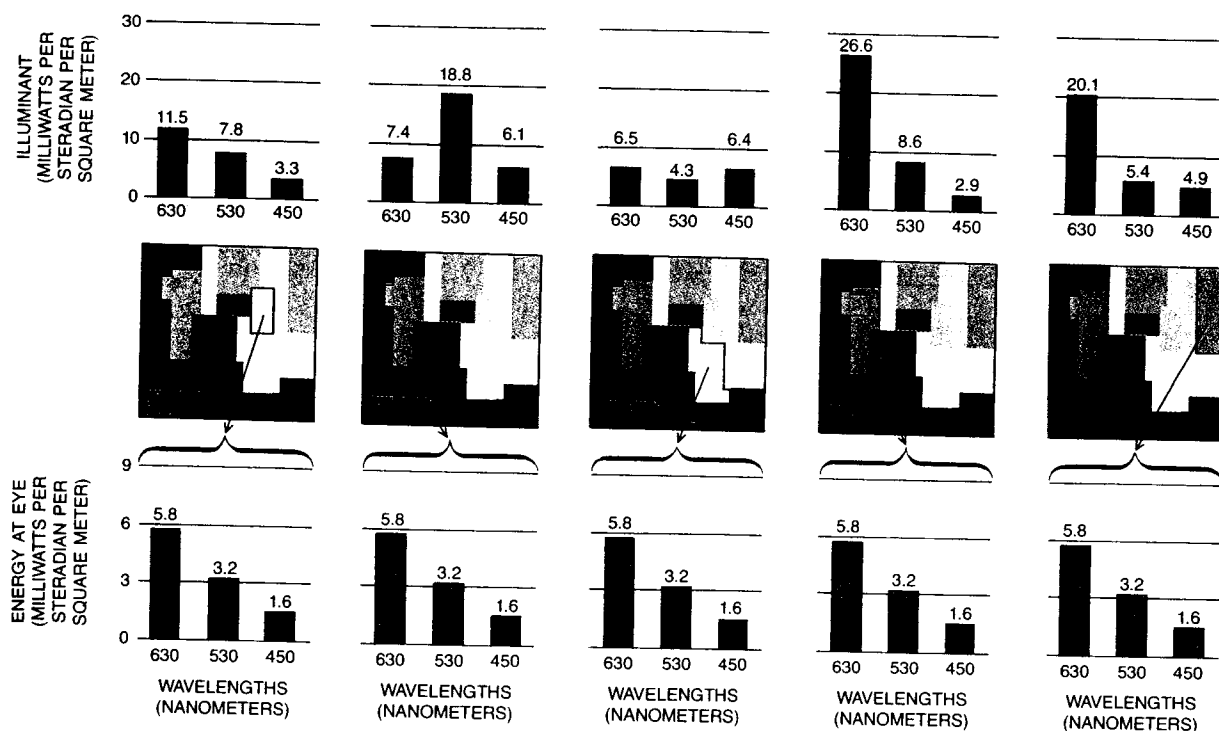effect on
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Figure 3.8 PROPORTIONS OF NARROW-BAND ILLU-MINANTS used to light the simplified Mondrian in the Munsell-chip matching experiments were adjusted as is shown by the bars at the top of this illustration so that five different areas of the Mondrian (*indicated by arrows*) sent to the observer's eye in successive matching trials the same triplet of energies: 5.8 flux units of long-wave light, 3.2 flux units of middle-wave light and 1.6 flux units of short-wave light. Figure 3.9 shows the Munsell chips that were selected in the constant illuminant to match the five Mondrian areas (gray, red, yellow, blue and green) that had sent to the eye exactly the same triplet of energies.

matter further by repeating the Mondrian-Munsell experiment in various ways so that the average spectral composition of the light reaching the eye from the Mondrian and its surround remains the same regardless of the spectral composition of the light needed to establish a constant triplet from area to area. We have done this in one case by surrounding the entire Mondrian with brightly colored papers selected in such a way that they exactly offset the average mixture of wave bands from the Mondrian itself and, more dramatically, by cutting the 17 areas of the Mondrian apart and placing them well separated on the backgrounds of offsetting color. Neither arrangement has any significant effect on the Munsell chips chosen to match the various areas of the Mondrian.

L et us return, then, to the search for the stimulus that guides us so accurately to the correct iden-tification of colors. If it is not a flux of radiant energy at the eye from each point in the field of view, what are the physical correlates of the light-nesses of objects on three separate wave bands, corresponding to the spectral sensitivities of the cone pigments? Can such a precise physical corre-late of lightness be demonstrated?

McCann, McKee and Taylor next measured the radiance, or energy at the eye, of the various Mon-drian areas and of the matching Munsell chips by using a photomultiplier in conjunction with a ver-sion of the retinex filters. Since the retinex-photo-multiplier combination integrates the flux of radiant energy over a broad band of wavelengths, the in-strument provides a value we call integrated radi-ance. McCann and his colleagues then obtained the integrated radiances from a large sheet of white paper placed under each of the experimental illu-minants that had been used to light the Mondrian in

the chip-matching experiments. If the integrated radiance from a Mondrian area is used as the numerator in a fraction and the integrated radiance from the white paper is used as the denominator, one obtains a value for integrated reflectance, which can be expressed as a percent.

The integrated reflectances for the various Munsell chips are determined in the same manner under the constant "white" illumination. This amounts to measuring the percentage of reflectance using detectors with the same spectral sensitivity as the visual pigments. The results show that the Munsell chip chosen by the eye to match a given Mondrian area will have approximately the same three integrated reflectances as the area. For example, the blue area in the Mondrian has a triplet of integrated reflectances (long, middle- and short-wave) of 27.3, 35.9 and 60.7 percent. The comparable values for

Figure 3.10 FURTHER ANALYSIS OF MATCHING EXPERIMENT begins to identify the basis on which the visual system makes the color match between the Mondrian area and the Munsell chip without regard to the flux each member of the pair sends to the eye. The efficiency with which a given area in the Mondrian reflects light in each of the three wave bands (*first column*) multiplied by the amount of energy striking that area in each of the wave bands (*second column*) yields the energy triplet that reaches the eye (*third column*). The three columns at the right contain comparable data for the Munsell chips selected as a match for the Mondrian areas.

the matched Munsell chip are 34.6, 38.5 and 57.1 percent (see Figure 3.11).

Finally, the integrated reflectances are "scaled" so that their equal spacing is consistent with the equal spacing of lightness sensations. The curve for this transformation is shown in Figure 3.12. Using this
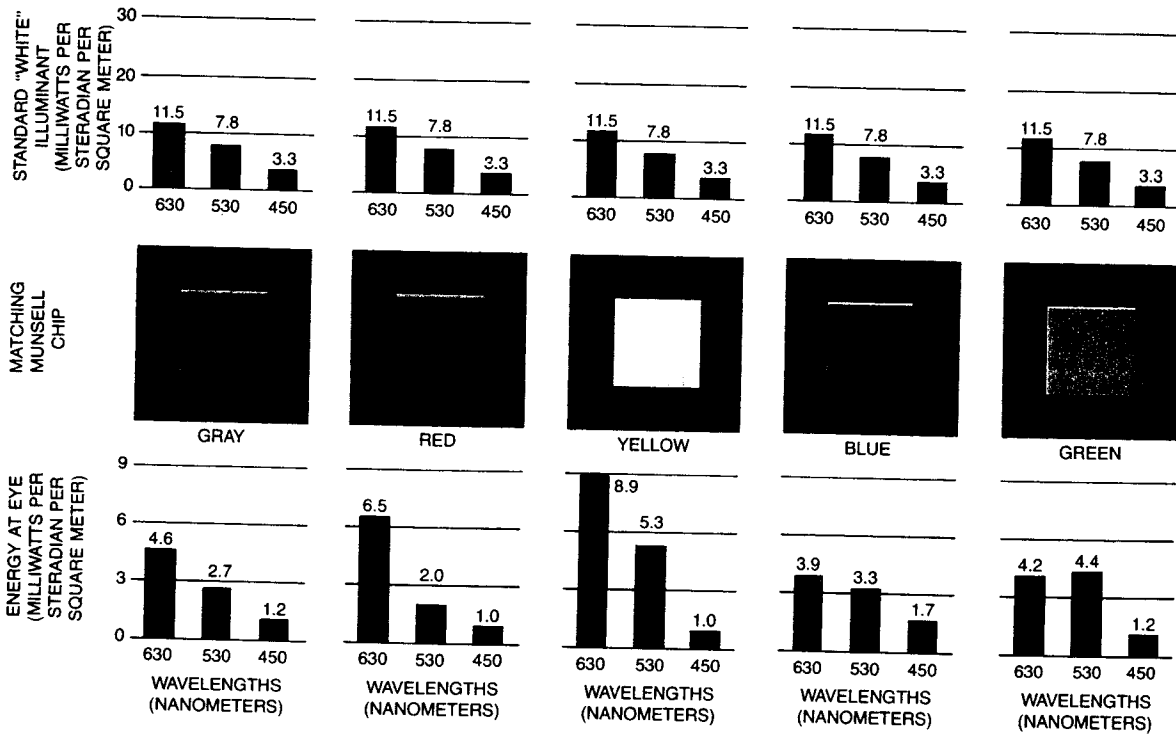
Figure 3.9 MUNSELL CHIPS SELECTED BY OBSERVERS to match the five Mondrian areas that had sent identical triplets of energy to the eye are reproduced. The Munsell book was illuminated with a constant spectral mixture of narrow-band illuminants (*bars at top*) and the chips were viewed within a constant gray surround. The energy that was sent to the eye by the selected Munsell chips is shown by the bars at the bottom of the illustration. It is evident that the match between the Mondrian areas and the Munsell chips is not made on the basis of the flux of radiant energy at the eye of the observer. What does cause the two areas to match is described in the illustrations that follow.

EXPERIMENTAL ILLUMINANTS

LEFT EYE

630
530
450

MONDRIAN

STANDARD "WHITE" ILLUMINANT

RIGHT EYE

630
530
450

MUNSELL
BOOK OF COLOR
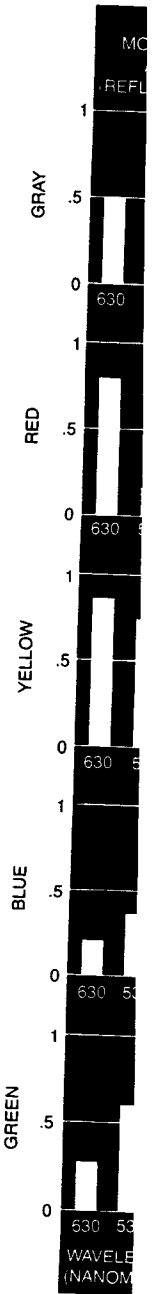
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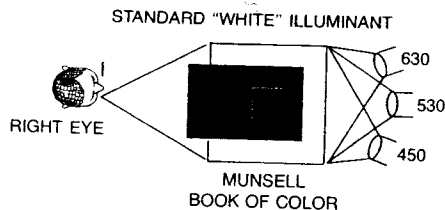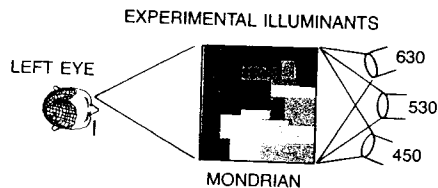
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4.4

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530   450

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MONDRIAN AREA (REFLECTANCE)

ILLUMINANT (MILLIWATTS PER STERADIAN PER SQUARE METER)

ENERGY AT EYE (MILLIWATTS PER STERADIAN PER SQUARE METER)

MUNSELL CHIP (REFLECTANCE)

ILLUMINANT (MILLIWATTS PER STERADIAN PER SQUARE METER)

ENERGY AT EYE (MILLIWATTS PER STERADIAN PER SQUARE METER)

GRAY

630 530 450

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630 530 450

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630 530 450

MATCHES

630 530 450

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630 530 450

=

630 530 450

RED

630 530 450

×

630 530 450

=

630 530 450

MATCHES

630 530 450

×

630 530 450

=

630 530 450

YELLOW

630 530 450

×

630 530 450

=

630 530 450

MATCHES

630 530 450

×

630 530 450

=

630 530 450

BLUE

26.6

630 530 450

×

630 530 450

=

630 530 450

MATCHES

630 530 450

×

630 530 450

=

630 530 450

GREEN

20.1

630 530 450
WAVELENGTHS (NANOMETERS)

×

630 530 450
WAVELENGTHS (NANOMETERS)

=

630 530 450
WAVELENGTHS (NANOMETERS)

MATCHES

630 530 450
WAVELENGTHS (NANOMETERS)

×

630 530 450
WAVELENGTHS (NANOMETERS)

=

630 530 450
WAVELENGTHS (NANOMETERS)

1 .5 0 (reflectance axis labels)

20 15 10 5 0 (illuminant axis labels)

Figure 3.11 ROLE OF REFLECTANCE and its psychophysical correlate, lightness, in guiding the eye to match Munsell chips with Mondrian areas was examined with the help of retinex filter-photomultiplier combinations that match the spectral sensitivity of the cone pigments. Under each combination of illuminants (*top*) the integrated curve, radiance, or flux, in each retinex wave band of a Mondrian area was compared with the integrated radiance of a sheet of white paper. The ratio of integrated radiances yields the integrated reflectance of the Mondrian area, expressed here in percent. For the matching Munsell chip a set of ratios was similarly determined (*bottom*).

curve, we see that the blue area in the Mondrian has a triplet of scaled integrated reflectances of 5.8, 6.5 and 8.1, whereas the corresponding values for the matching Munsell chip are 6.4, 6.7 and 7.9. If we study the five areas that successively sent identical triplets of energies to the eye and compare their scaled integrated reflectances with those of their matching Munsell chips, we find that all the values are in excellent agreement. In others words, in the triplets of integrated reflectances we have identified a highly accurate physical correlate of color sensations. The data fall along the 45-degree line that describes the locus of perfect correlation (see Figure 3.13).

We have sought a physical correlate for lightness, and we have found that the scaled integrated reflec-

SCALED
INTEGRATED
REFLECTANCES

5.8

6.5

8.1

6.4

6.7

7.9
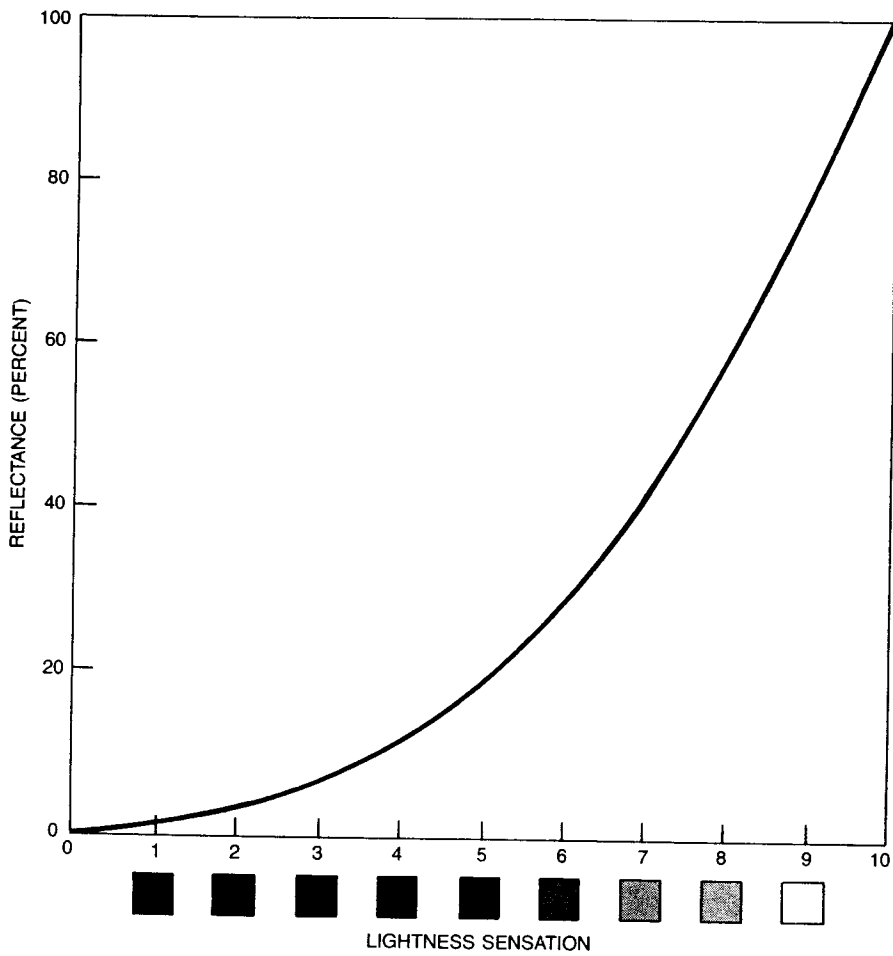
Figure 3.12 SENSATION OF LIGHTNESS is plotted on an equal-interval scale. Observers are shown a sheet of white paper (9) and a sheet of black paper (1) and are then asked to choose a sheet of paper whose shade of gray lies halfway between the two. The selection is the gray labeled 5. Similar selections are made to determine the locations of midpoints between 1 and 5 and between 5 and 9 and so on until the equal-interval scale is filled. The end values 0 and 10 are extrapolations. The curve, plotted by measuring the reflectances of the various selected papers, makes it possible to convert values of integrated reflectance into values of scaled integrated reflectance, as given in the far right column of Figure 3.11.

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tances of the five areas that sent identical triplets of fluxes to our eyes are the same as those of the matching Munsell chip. This correlation enables us to use scaled integrated reflectances as a measured lightness equivalent. The problem now shifts to one of how the eye derives the lightness that corresponds to the reflectances of objects in each wave band.

It is one thing to measure a triplet of lightness equivalents using a retinex filter coupled to a photo-

multiplier; it is quite another for the eye to determine lightnesses in the unevenly lighted world without reference sheets of white paper. I described above the ability of an isolated receptor system — the hypersensitive system of rod vision — to classify objects correctly according to their inherent reflectivity regardless of whether the objects happened to be in a brightly or a dimly lighted region of visual space. The ability of one receptor system to work in this way makes it plausible that the other three

Figure 3.13 AGREEMENT IN SCALED INTEGRATED REFLECTANCES between Mondrian areas and Munsell chips is summarized for all three wave-band systems. The scaled integrated reflectances of five Mondrian areas and matching chips were determined as in Figure 3.11. This graph plots triplets of scaled integrated reflectances of five Mondrian areas that sent identical fluxes to the eye against scaled integrated reflectances of matched Munsell chips. The dots collectively represent correspondence for all three retinex wave bands; any particular dot denotes the degree of correspondence on one retinex wave band between a Mondrian area and a Munsell chip.

systems of normal daytime vision possess the same ability, each system viewing the world through a broad but restricted region of the spectrum, the regions we duplicate with retinex filters. Each system forms a separate lightness image of the world. The images are not mixed but compared. The comparison of lightnesses at each area gives rise to the range of sensations we know as color.

How could the biological system generate a hierarchy and spacing of lightness values given only the flux from each point in a scene and knowing nothing about the pattern of illumination and nothing about the reflectances of objects? The scheme I am about to describe is the most general we have found that surmounts these limitations; its physiological embodiment could take many forms.

Let me begin by pointing out the significance of edges in defining objects or areas in a scene. If a sheet of white paper is lighted strongly from one side, we see no discontinuity in color from one side to the other. Let us now imagine two light detectors positioned to measure the luminance from two different places on the paper. If the illumination is nonuniform, the luminances of the two places will

of course be different. As the two detectors are moved closer together the luminances approach the same value and ratio of the two outputs approaches unity. If, however, the two detectors bridge the boundary between two areas that differ abruptly in reflectance, such as would be the case with even a pale gray square on the white paper, the ratio of the outputs of the two detectors will approach the ratio of the two reflectances [The ratio is subjected to a threshold test: any ratio to be regarded as a change must vary from unity by more than some small threshold amount, plus or minus .003 in the computer program]. Thus the single procedure of taking the ratio between two adjacent points can both detect an edge and eliminate the effect of nonuniform illumination. If we process the entire image in terms of the ratios of luminances at closely adjacent points, we can generate dimensionless numbers that are independent of the illumination. These numbers give the ratio of reflectances at the edge between adjacent areas; the reflectances themselves are not yet ascertained.

In order to determine reflectances we need to relate all these ratios of reflectances in the field of view. Given the ratio of luminances at the edge between a first area and a second one, we multiply it by the ratio of luminances at the edge between the second area and a third. This product of ratios approaches the ratio of reflectances between the first and third areas, regardless of the distribution of illumination. Similarly, we can obtain the ratio of reflectances of any two areas in an image, however remote they are from each other, by multiplying the ratios of all the boundaries between the starting area and the remote area. We can also establish the ratio of the reflectance of any area on the path by tapping off the sequential product reached at that area (see Figures 3.14 and 3.15).
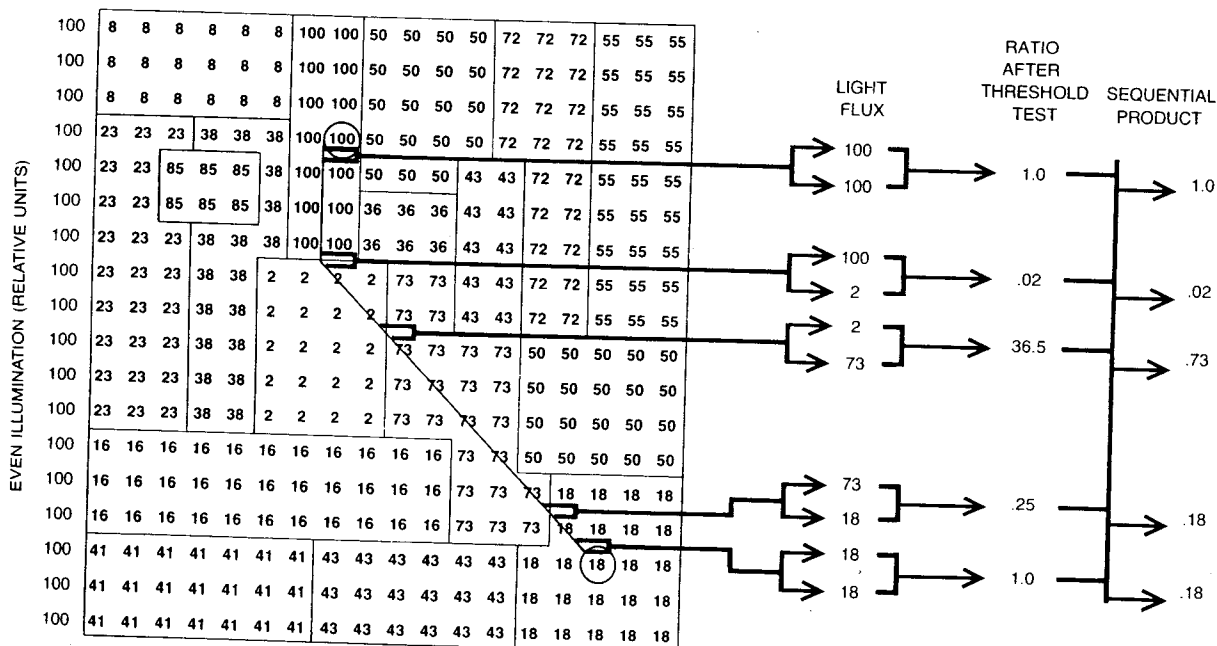

Figure 3.14 SCHEME FOR EYE'S METHOD of discovering lightness in complex images is depicted here and in Figure 3.15. The numbers inside the schematic Mondrian represent the long-wave integrated radiances coming from each area of a display that is evenly lighted. The long-wave retinex system independently "measures" the long-wave integrated radiance, point by point, as if along an arbitrary pathway (color). The flux at each successive closely spaced pair of points is converted into a ratio. If the ratio does not vary from unity by some threshold amount, it is regarded as being "unchanged" and is set to equal unity. A second threshold-tested ratio along the same pathway is multiplied by the first ratio to give a sequential product that is both the model's response for that point and the signal sent along to be multiplied by the next ratio. When the path crosses an edge between two lightnesses, there is a sharp change in the threshold-tested ratio and hence a similar change in the sequential product.
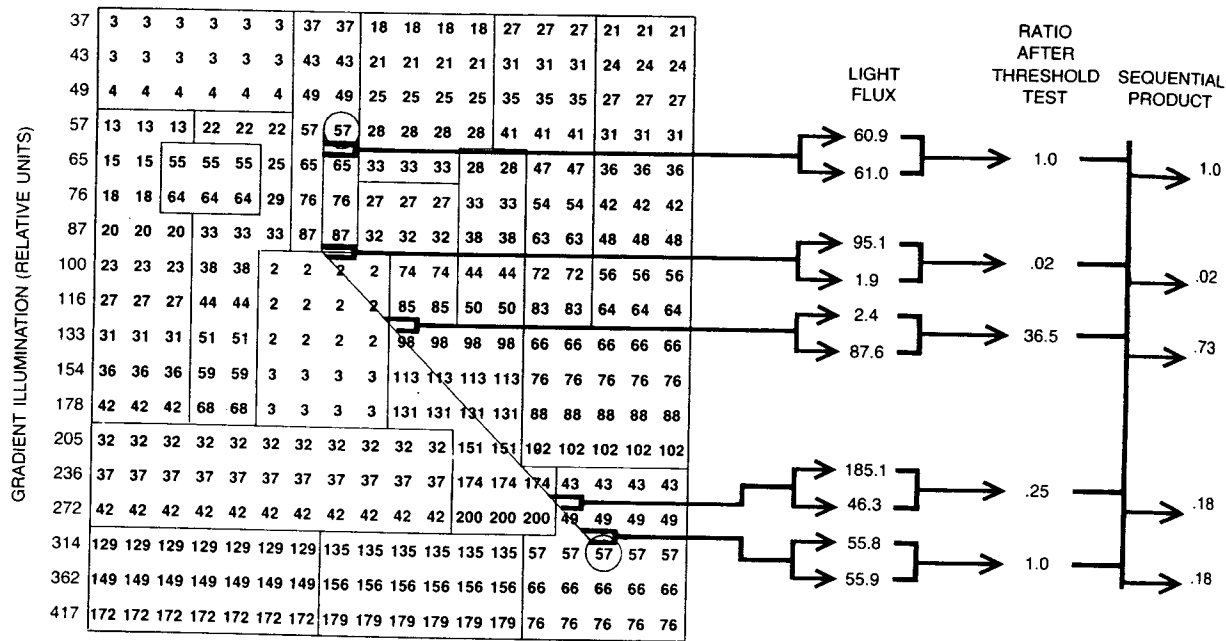
GRADIENT ILLUMINATION (RELATIVE UNITS)

```
37 |  3   3   3   3   3   3 | 37  37 | 18  18  18  18 | 27  27  27 | 21  21  21
43 |  3   3   3   3   3   3 | 43  43 | 21  21  21  21 | 31  31  31 | 24  24  24
49 |  4   4   4   4   4   4 | 49  49 | 25  25  25  25 | 35  35  35 | 27  27  27
57 | 13  13  13  22  22  22 | 57 (57)| 28  28  28  28 | 41  41  41 | 31  31  31
65 | 15  15  55  55  55  25 | 65  65 | 33  33  33  28  28 | 47  47 | 36  36  36
76 | 18  18  64  64  64  29 | 76  76 | 27  27  27  33  33 | 54  54 | 42  42  42
87 | 20  20  20  33  33  33 | 87  87 | 32  32  32  38  38 | 63  63 | 48  48  48
100| 23  23  23  38  38   2   2 |  2 | 74  74  44  44 | 72  72 | 56  56  56
116| 27  27  27  44  44   2   2   2 |  2 | 85  85  50  50 | 83  83 | 64  64  64
133| 31  31  31  51  51   2   2   2 |  2 | 98  98  98  98 | 66  66  66  66  66
154| 36  36  36  59  59   3   3   3 |  3 |113 113 113 113 | 76  76  76  76  76
178| 42  42  42  68  68   3   3   3 |  3 |131 131 131 131 | 88  88  88  88  88
205| 32  32  32  32  32  32  32  32  32  32 |151 151 |102 102 102 102 102
236| 37  37  37  37  37  37  37  37  37  37  37 |174 174 174 | 43  43  43  43
272| 42  42  42  42  42  42  42  42  42  42  42 |200 200 200 | 49  49  49  49
314|129 129 129 129 129 129 129 |135 135 135 135 135 135 | 57  57 (57) 57  57
362|149 149 149 149 149 149 149 |156 156 156 156 156 156 | 66  66  66  66  66
417|172 172 172 172 172 172 172 |179 179 179 179 179 179 | 76  76  76  76  76
```

LIGHT FLUX	RATIO AFTER THRESHOLD TEST	SEQUENTIAL PRODUCT
60.9 / 61.0	1.0	1.0
95.1 / 1.9	.02	.02
2.4 / 87.6	36.5	.73
185.1 / 46.3	.25	.18
55.8 / 55.9	1.0	.18

Figure 3.15 MORE REALISTIC CASE OF GRADED ILLU-MINATION is handled equally well by the sequential-product method to arrive at the same reflectance value of .18 for the brown area at the end of the path, even though here the long-wave retinex system receives as much flux from the middle of the brown area (57) as it does from the middle of the white area (57). (The white and brown areas are shown in color in Figures 3.6, 3.7 and 3.8.) The scheme hence provides a means for arriving at computed reflectance independent of flux and without resort to white cards as standards. Precise values of light flux along pathway in this diagram were derived from a computer program that works with 75 values between every two values printed within Mondrian.

We are now coming close to the answer to the question: How can the eye ascertain the reflectance of an area without in effect placing a comparison standard next to the area? The sequential product can be used as a substitute for the placement of two areas adjacent to each other, thus defining a photometric operation feasible for the eye.

The remaining task is to suggest how the eye can discover the area of highest reflectance in the field of view and then decide whether that area is actually white or some other color. In the model we have proposed, sequential products are computed along many arbitrary pathways that wander through the two-dimensional array of energies on the model's "retina." Since the pathways can begin anywhere, not just in regions of the highest reflectance, the first value in any sequence is arbitrarily assumed to be 100 percent. [Thus, in Figure 3.14, the path is started in the white area, where the flux of radiant energy is 100. By the time the path reaches the brown area at the lower right, the prod-uct is .18. (The corresponding colored areas are shown in Figures 3.6, 3.7 and 3.8.) The retinex system has thus determined that the brown area reflects 18 percent as much long-wave energy as the white area. Any other path ending in the brown area would yield the same result as long as it had been through the white area. By averaging the responses for each area, as computed by many arbitrary paths, the long-wave retinex system arrives at a single reflectance value for each area, which designates perceived lightness. Middle- and short-wave retinex systems compute their own sets of lightness values. Comparison of triplet of lightnesses for each area provides sensation of color.] Because of this deliberately adopted fiction the sequential product becomes greater than unity whenever the path reaches an area whose reflectance is higher than that of the starting area.

The attainment of a sequential product greater than unity indicates that the sequence should be started afresh with the new area of high reflectance

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SEQUENTIAL
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→ 1.0

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taken as being 100 percent. This procedure is the heart of the technique for finding the highest reflectance in the path. After the path reaches the highest reflectance in the scene, each of the sequential products computed thereafter becomes a fraction of the highest value. A satisfactory computer program has been designed to study the number of paths, their lengths and convolutions, the threshold values for recognizing edges and, perhaps most important, how to utilize all the pathways starting in all areas.

The biological counterpart of this program is performed in undetermined parts of the pathway between the retina and the cortex. The process that corresponds to computing sequential products does not involve the averaging of areas or the averaging of flux. It does, however, call for an arithmetic that extends over the entire visual field. Furthermore, since the relevant phenomena are seen in a brief pulse of light, all the computations and conclusions about lightness must be carried out in a fraction of a second without dependence on eye movement. With a single pulse, eye movement, by definition, is not necessary. With continuous illumination the normal quick motions of the eye probably serve to maintain the freshness of the process.

With our computer model we can obtain a triplet of lightnesses for each area in the color Mondrian that corresponds closely to the lightnesses one would measure with a combined retinex filter and photomultiplier. The color corresponding to any given triplet can be visualized with the aid of the color "solid" we have built, in which the Munsell colors are located in three dimensions in "lightness-color space" according to their lightness values measured in three wave bands through retinex filters. [Each plane in Figure 3.16 is the locus of colors possible with a constant short-wave lightness. For example, the fifth plane from the bottom shows the variety of color sensations from all possible long- and middle-wave lightness values, when those values are combined with a short-wave lightness of 5. The colored squares are samples taken from *The Munsell Book of Color*. In general the blank areas on each plane represent regions where colors, if they were produced at all, could be produced only by fluorescent dyes.]

In normal images the sensation of white light will be generated by any area that is placed at the top of the lightness scale by all three retinex systems. On the other hand, an area that stands at the top of only two of the three lightness scales will be seen as some other color. Hence an area that is at the top of
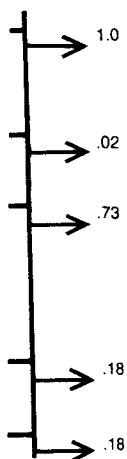
the lightness scale in the long- and middle-wave systems but is surpassed in lightness by some other area in the short-wave system will be seen not as white but as yellow. A similar intercomparison of triplets of lightnesses at the same place within each scene provides the sensation of color, area by area, in spite of unpredictable variations in illumination.

If one looks at black-and-white photographs taken through retinex filters, one sees a dramatic difference in lightness for most objects between the photograph representing the short-wave system and either of the photographs representing the other two systems. And yet it is the comparatively small differences between the long-wave and the middle-wave lightnesses that are responsible for the experience of vivid reds and greens.

Such reliable and sensitive responsiveness to small lightness differences provides the basis for the colors seen under anomalous conditions far removed from those the eye has evolved to see. Two examples of interest are the color of a spot of light in a total surrounding area devoid of light and the spectrum of colors produced by a prism.

One can readily measure the flux at the eye from a spot of light in a void. By changing the flux it is possible to estimate the corresponding change in perceived lightness. What one finds is that the estimated lightness changes only slowly with enormous changes in flux. For example, decreasing the flux by a very large amount will be seen as a very small reduction in lightness. If the spot of light is composed of a narrow band of long wavelength, say 600 nanometers, one can expect all three cone receptors to absorb the radiation in some degree, but significantly more radiation will be absorbed by the long-wave cones than by the other two kinds. [In arbitrary units the long-wave pigment might absorb 80 units, the middle-wave pigment 20 units and the short-wave pigment a few tenths of a unit at most.] When the three values are read on a scale of perceived lightness, the three lightnesses are 9 on the long-wave system, 8.5 on the middle-wave system and 7.5 on the short-wave system (see Figure 3.17). This combination of lightnesses is seen as a light reddish orange, a color not commonly perceived under ordinary conditions unless the surfaces are fluorescent. The spectrum, a strikingly anomalous display, can be regarded as a series of three laterally displaced continuous gradients involving both the properties of spots and the properties of areas. From these properties it is possible to predict the colors of the spectrum, whereas it is not possible, as we have
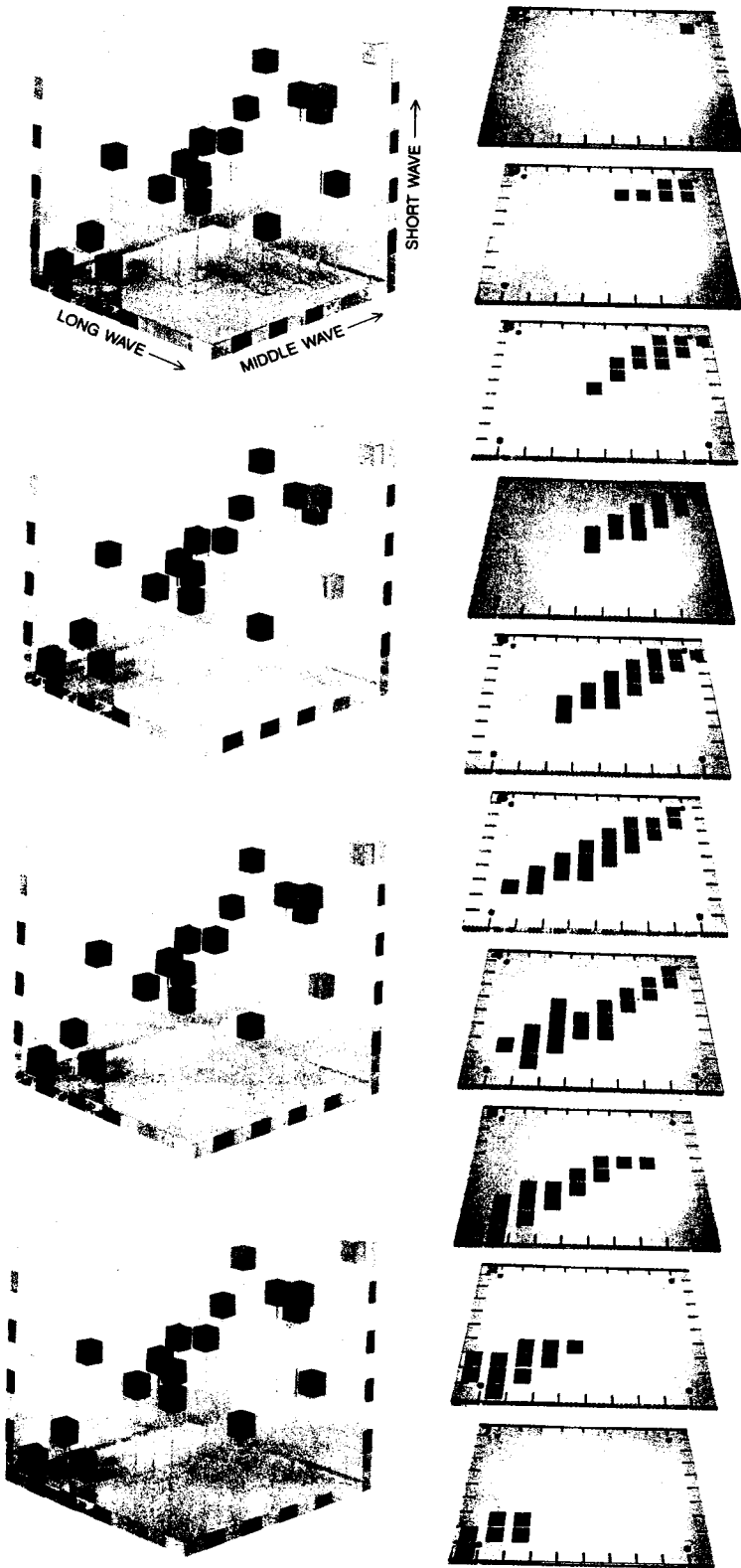
Figure 3.16 COLOR "SOLID" lo-
cates all perceivable colors, in-
cluding white and black. The
position of a color in this three-
dimensional space is determined
by the triplet of lightness com-
puted by the eye for each area.
The color photograph at the top
left shows the location of repre-
sentative colors throughout the
space. The direction of increasing
lightness along each axis is shown
by the arrows. The three black-
and-white photographs of the
color solid were taken with re-
tinex filter-film combinations.
They show the lightness values of
the representative colors as they
would be perceived separately by
the eye's long-wave (top), middle-
wave (middle) and short-wave
(bottom) visual pigments. The set
of 10 color pictures at the right
represents horizontal planes cut
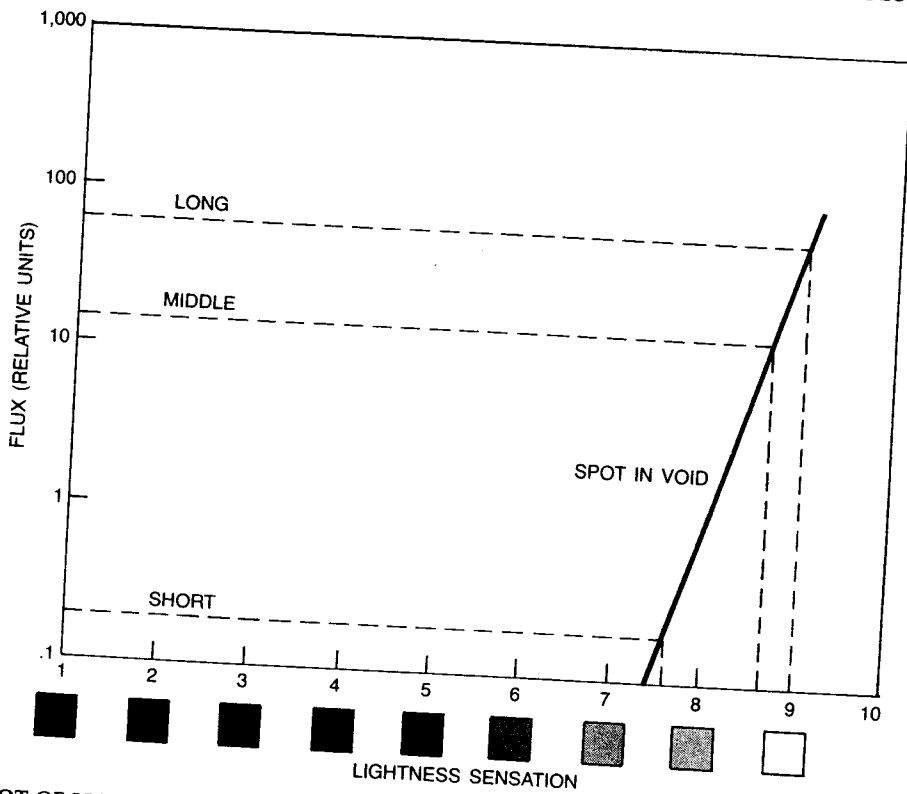through the three-dimensional
color space.

Figure 3.17 SPOT OF LIGHT IN A VOID, that is, a single spot of narrow-band light viewed in an otherwise totally dark environment, has a color that would seem to depend solely on its wavelength. The color can also be explained, however, by the retinex theory in terms of lightness as seen, to attribute a specific spectral composition to perceived by the eye's three receptor systems. Psychophysical measurements show that when the eye is presented with a spot of light in a void, the perceived lightness is changed only slightly by very large changes in flux, as is indicated by the straight line.

seen, to attribute a specific spectral composition to the radiance from a colored area in everyday life.

Perhaps the first observation pointedly relevant to the mechanism of color formation in images is not Newton's spectrum but the phenomenon of colored shadows, described in 1672 by Otto von Guericke. "This is how it happens," he wrote, "that in the early morning twilight a clear blue shadow can be produced upon a white piece of paper [by holding] a finger or other object . . . between a lighted candle and the paper beneath." This important experiment, we now know, depicts an elementary example of generating three different lightnesses on the three receptor systems. A diagram of this experiment with long-wave ("red") light and white light appears in Figure 3.18. Here the color of the shadow is blue-green. [In the analysis at the right in Figure 3.18 it is assumed that one projector sends white light to the screen. The other projector, equipped with a red filter, sends only long wavelengths to the screen. Assume that the white light contributes 100 arbitrary units of flux to each of the short-, middle- and long-wave receptors. The long-wave flux is absorbed by the three receptor systems in different proportions: 100 units are absorbed by the long-wave system, 50 by the middle-wave system and five by the short-wave system. (A small amount of scattered long-wave light also appears in the shadow.) The third column of boxes shows the combined amounts of flux from both sources absorbed by each receptor system. The fractions represent the ratio at edges of the flux from within the shadow divided by the flux from outside. The fourth column shows the lightness on each receptor system. The lightness of the lightest place in the scene for each receptor system will be near the top of the lightness scale, being determined by the flux

Figure 3.18

ABSORBED FLUX (ARBITRARY UNITS)

	FROM "WHITE" ILLUMINATOR	FROM LONG-WAVE ("RED") ILLUMINATOR (SCATTER)	FROM TWO ILLUMINATORS COMBINED	LIGHTNESS	COLOR
SHORT-WAVE RECEPTOR SYSTEM	100	5 (.05)	105 / 100; 100/105	VERY LIGHT / LIGHT	
MIDDLE-WAVE RECEPTOR SYSTEM	100	50 (.5)	150 / 101; 101/150	VERY LIGHT / MEDIUM-LIGHT	
LONG-WAVE RECEPTOR SYSTEM	100	100 (1.0)	200 / 101; 101/200	VERY LIGHT / DARKER	

BLUE-GREEN SHADOW

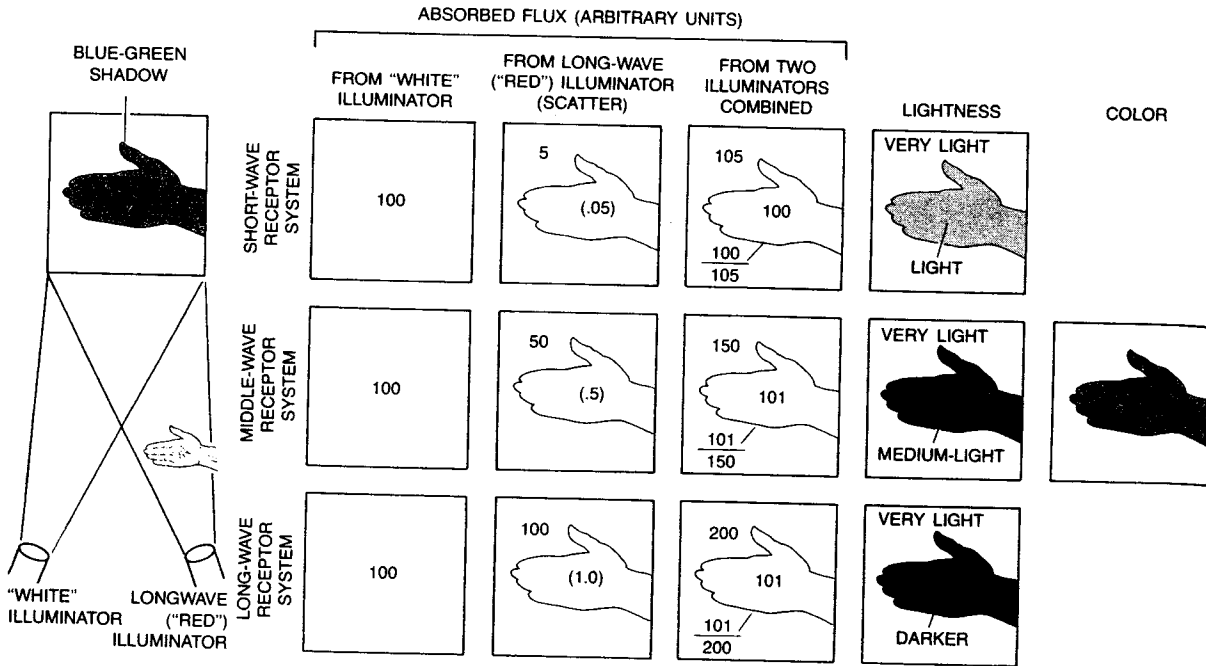"WHITE" ILLUMINATOR   LONGWAVE ("RED") ILLUMINATOR

Figure 3.18 BLUE-GREEN COLORED SHADOW is seen when a hand or some other object is placed in the beam of a projector that is sending long-wave ("red") light to a screen while the screen is illuminated by a beam of white light. The author regards Otto von Guericke's description in 1672 of seeing colored shadows made by candlelight as the first observation pointedly relevant to the mechanism of image and color formation.

of radiant energy in the same way that a spot has its lightness determined by flux. Triplet of lightnesses within the shadow falls in the region of color space that the eye perceives as being blue-green.] The diagram thus shows that the triplet of lightnesses in the shadow corresponds to the blue-green color one would predict for it from its position in lightness-color space.

One can now understand the red-and-white images of our early work as a procedure that carries the colored shadow to a richly variegated family of colors no longer in shadows but in images. The colors seen in a red-and-white projection can be readily predicted by extending the analysis followed in predicting the color of von Guericke's shadow. To demonstrate this point we reproduce in Figure 3.19 the "red" and "green" separation images used in making a red-and-white multicolored projection. (In this demonstration no attempt is made to reproduce the colors seen in the actual multicolored image.) The red-and-white projection was photographed through long-, middle- and short-wave re-tinex film-filter combinations. The three images are reproduced below the pair of long- and middle-wave separation images that were superposed to make the red-and-white image. [The long-wave record was projected onto a screen with a long-wave (red) filter in the beam of light. The middle-wave record was projected in superposition onto the same screen in the light of a tungsten-filament lamp.] The significant point is that when the eye views the red-and-white images on the screen with its own retinex system, it is provided with a triplet of lightnesses for each part of the scene that resembles the triplet it would obtain if it viewed the original scene directly. In this important meeting point of the blue-green shadows with the colored images, provided by the red-and-white display, the extended taking and multiplication of ratios determine the lightness of each small area. Finally, all these principles are applied in everyday ternary vision, which creates a distinct lightness image for each of the three sensitive systems and compares them in order to generate color.
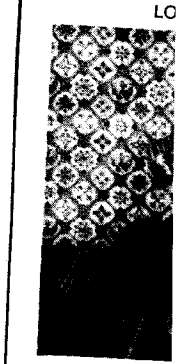
LONG-WAVE

Figure 3.19 RE projections sh triplet of light with observed half) are reprod wave (right) se life. The retin long-wave at t short-wave at tl

The train ments star that the relati jectors can be of the various simplistic expl and surround a independent l systems that u

LONG-WAVE ("RED") SEPARATION RECORD

MIDDLE-WAVE ("GREEN") SEPARATION RECORD

RED FILTER

RED-AND-WHITE
MULTICOLORED
PROJECTED
IMAGE

(NO FILTER)

RETINEX FILTERS

LONG-WAVE RETINEX RECORD

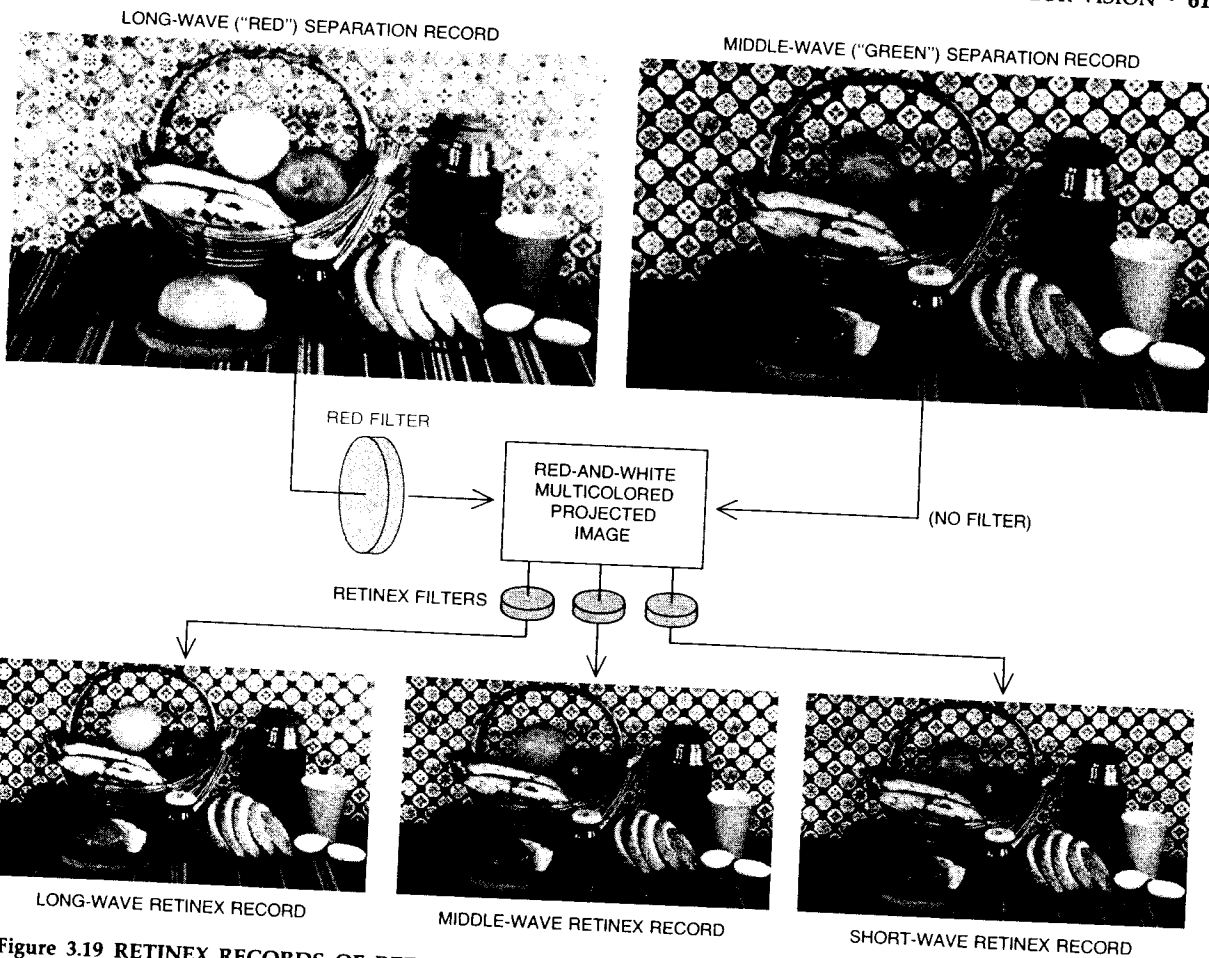MIDDLE-WAVE RETINEX RECORD

SHORT-WAVE RETINEX RECORD

Figure 3.19 RETINEX RECORDS OF RED-AND-WHITE projections show that red-and-white images produce a triplet of lightnesses for each part of the scene consistent with observed color sensations. The two photographs (*top half*) are reproductions of the long-wave (*left*) and middle-wave (*right*) separation records taken of the original still life. The retinex records are reproduced at the bottom: long-wave at the left, middle-wave in the middle and short-wave at the right. The colors seen in red-and-white projections are those one would expect from their triplets of lightnesses. The apple is light on the long record and darker in the middle and short records. The orange is lightest on the long record, intermediate on the middle record and darkest on the short. With one's own retinex systems, one can see a blue cup, a brown straw basket and pale yellow bananas with lightness differences so small as to challenge photoengraving process used to reproduce photographs.

The train of interlocking concepts and experiments started 25 years ago with the observation that the relative energies of the red-and-white projectors can be altered without changing the names of the various colors. This observation negated the simplistic explanation in terms of contrast, fatigue and surround and led to the fundamental concept of independent long- and short-wave image-forming systems that ultimately evolved to the concept of three independent retinex systems and to the Mondrian demonstration. The concept of the percentage of available light on each wave band as a determining variable and the technique of measuring it evolved to the concept that lightnesses maintain an independent rank order on long- and short-wave bands. This measuring technique in turn evolved from a projected black-and-white image to an arrangement of colored papers in the color Mondrian.

The manifest stability and constancy of the lightnesses of all the papers of the Mondrian when a single wave band illuminates it with varying intensity dramatizes the concept that every colored paper has three reflectances on three wave bands and that these reflectances are somehow connected with the biological characteristic: lightnesses.

A black-and-white Mondrian taught that nonuniformity of illumination, size and shape of area and length of edges were basically irrelevant to lightness. What was needed was a far-reaching, edge-reading arithmetic: the sequential product of ratios at edges. For the color Mondrian the ratio at edges was early recognized as requiring a ratio of the integrals of the product at each wavelength of the absorbance of the cone pigment times the reflectance of the colored paper times the illuminants. Separate integrals were taken over the wave bands of the three cone pigments. In a long series of binocular comparison-and-selection observations the quantity satisfying the integral was shown to be impressively well correlated with lightness, particularly after the realization that the scale, or spacing, of the reflectance integral should be made to correspond with the spacing of the biological quantity lightness. This led to the designation "scaled integrated reflectance" as the external partner to which the retinex system relates the internal partner: constructed lightness.

Color can be arranged in the lightness solid with long-, middle-and short-wave axes of lightness. All visible colors reside in this solid independent of flux, each color having a unique position given by the three axial values of lightness. It should be remembered that the reality of color lies in this solid. When the color Mondrian is nonuniformly illuminated, photographed and measured, reflectance in the photograph no longer correlates with the color but the lightness does. The three sets of ratios of integrals at edges and the product of these integrals within a set emerge as the physical determinants in the partnership between the biological system and areas in the external world.

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