

THE PERCEPTION OF NEUTRAL COLORS

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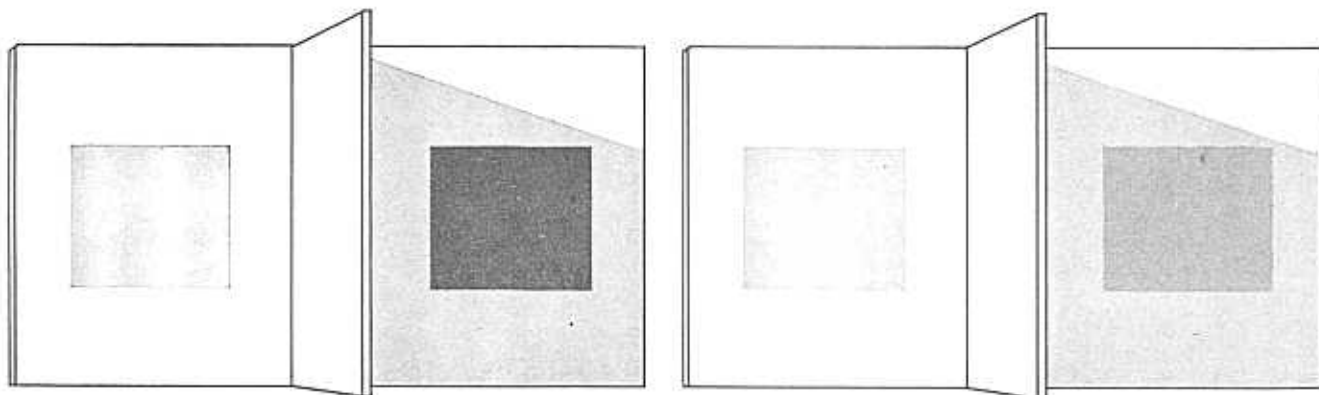
Most investigations of color perception deal with the relation between the spectral composition of light—the assortment of wavelengths in it—and the color sensations it evokes. But there is a family of colors the quality of which does not depend on wavelength or combinations of wavelengths. These are the achromatic, or neutral, colors—white, the various grays and black—which differ from one another only in degree of lightness or darkness. The scale of lightness, in other words, is the only dimension of the neutral colors, although it is one dimension (along with hue and saturation) of the chromatic colors as well. The perception of neutral colors is therefore a basic problem in visual perception that needs to be understood in its own right and that at the same time has implications for color vision in general.

The fact that lightness does not depend on a property of light itself is not

only a semantic paradox but also a major complication in the study of neutral-color perception. Light can appear dim or bright but not light or dark. It can be blue or yellow or red but not gray. Lightness or darkness is a property of surfaces, and the investigator of neutral-color perception must concern himself with white or gray or black surfaces. Now, the physical property of a surface that corresponds to a perceived neutral color is reflectance. A surface deserves to be called white if it reflects diffusely about 80 per cent of the visible light of any wavelength that falls on it, and it is called black if it reflects only 4 or 5 per cent of the incident light. The various shades of gray range between these extreme reflectance values. The big problem in understanding the perception of neutral colors is that the amount of light reflected by a neutral surface depends not only on its reflectance but also on the intensity of the illuminating light. As the illumination varies over a broad

range, the intensity of the light reflected by a surface of a given neutral color will vary just as much. The light message that is received from a reflecting surface is therefore an ambiguous clue to its reflectance—to its "actual" color.

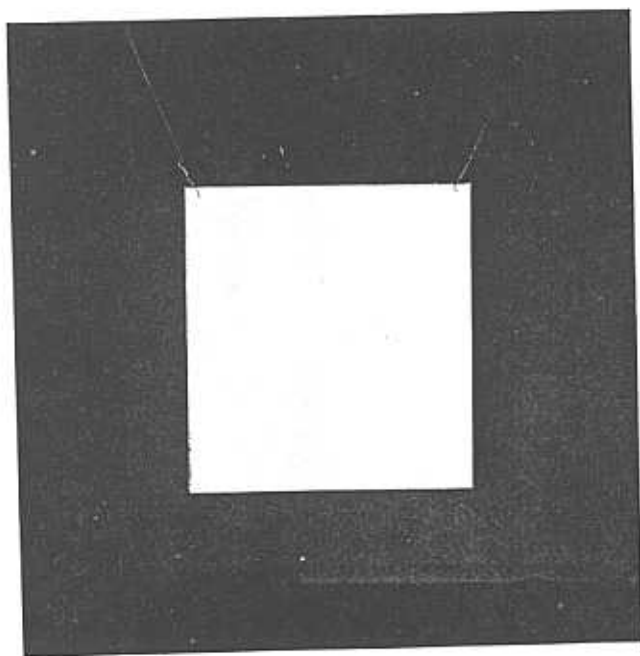
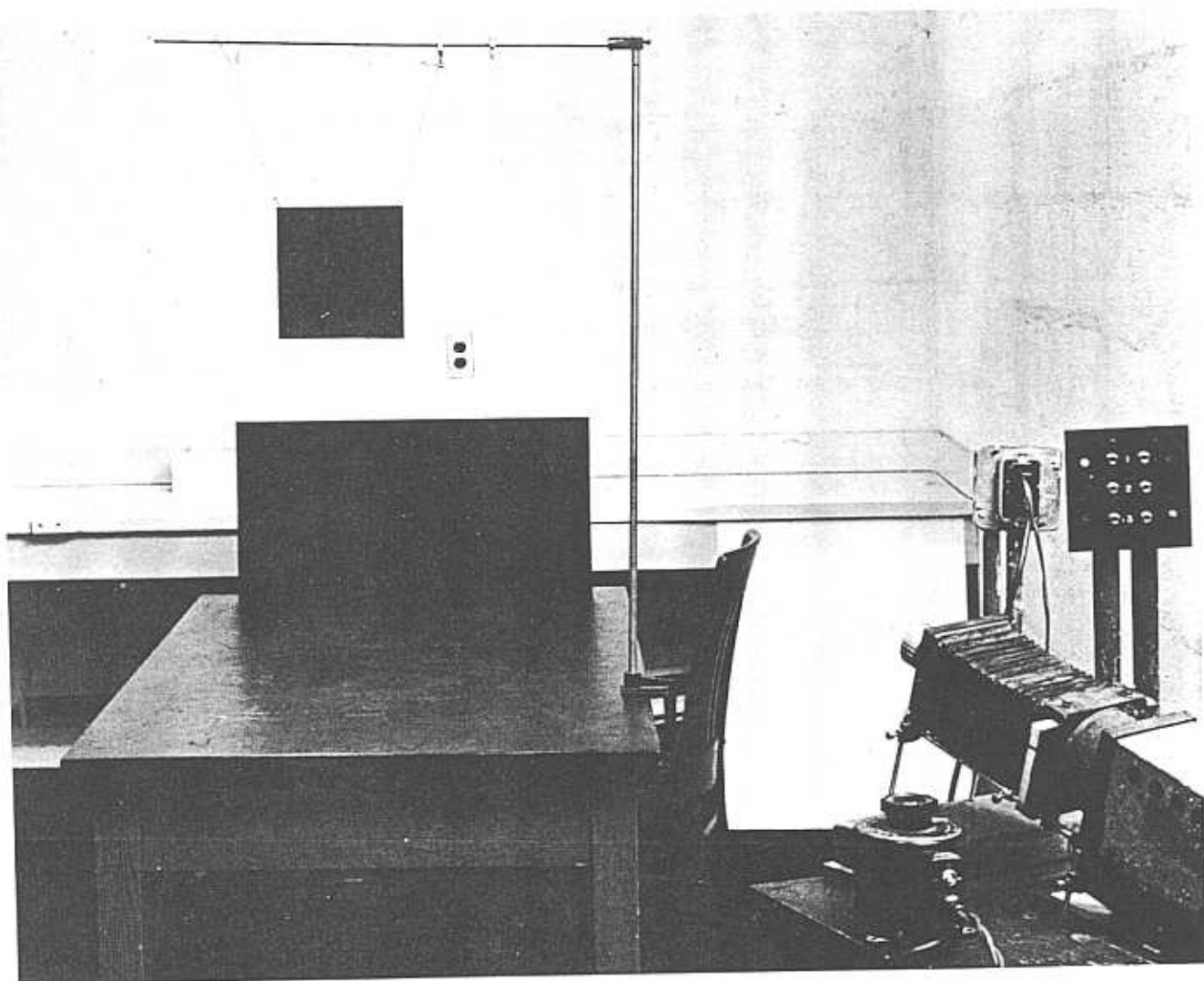
How then can one account for the fact that perceived neutral colors are usually in good agreement with the reflectance of the surface on which they appear—that a dark gray object, for example, tends to look dark gray in all sorts of light? This "constancy" effect, as psychologists call it, can be simply demonstrated by an experiment that David Katz, a German psychologist, devised more than 30 years ago. Two identical gray samples are fastened to a white background and a screen is so placed that it casts a shadow on one of the samples and on its surround [see illustration below]. The sample in the shadow does indeed appear to be a somewhat darker gray than the sample in direct illumination. That is to say,



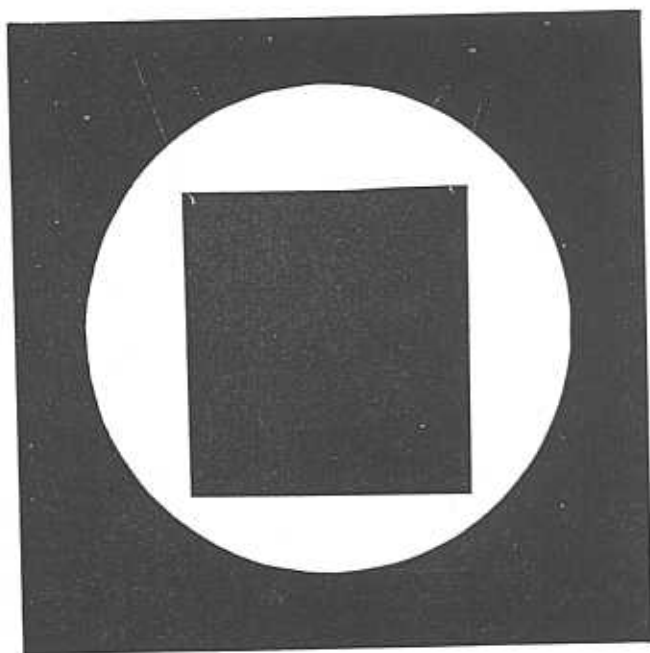
CONSTANCY of neutral colors is demonstrated by this experiment. When one of two identical gray samples is placed in shadow, it looks to an observer only a little darker than its brightly illuminated counterpart although, as the drawing shows, it reflects a lot less light (*left*). The color of the shadowed sample is then

lightened until it looks the same as the well-lighted one; it still reflects much less light (*right*). In each situation constancy is at work, making the grays appear more equal than the actual light intensities they reflect would warrant. The drawing reproduces these actual light intensities, not the apparent colors of the samples.

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IMPRESSIVE DEMONSTRATION of constancy can be given with the setup illustrated in the top photograph. A dark gray sample suspended before a light-colored wall is illuminated by a projection lantern. When the sample hangs alone, any change in room illumination or lantern intensity changes its apparent color. At the



bottom left, for example, it appears almost white. But if a white surround is placed behind the sample within the lantern beam, the sample immediately looks gray again (*bottom right*). It stays gray in spite of changes in the lantern intensity or room illumination. The bottom photographs simulate the apparent colors of the sample.

constancy is not complete. But the shadowed sample by no means looks as much darker as the difference in the actual light intensities reflected by the two samples would warrant, which is to say that there is a constancy effect. When the shadowed sample is replaced by a patch of lighter gray so chosen that the two surfaces appear to be the same in spite of their different illuminations, the shadowed sample will still reflect a good deal less light than the directly illuminated one. This difference in the actual light intensity compatible with apparent equality of color represents the constancy effect. Any explanation of this effect must account eventually not only for its presence but also for its incompleteness as demonstrated in the first part of the experiment.

For a long time the standard explanation of constancy has been that the viewer takes illumination into account when he evaluates the intensity of the light reflected by a surface. The difficulty with this is that illumination is never given independently. It manifests itself only by way of the light that the various surfaces in the visual field reflect. One variable, the intensity of the reflected light, depends on both the incident illumination and the reflectances of the surfaces—and is in turn the only direct clue to both of these factors.

The Katz demonstration had the virtue of simulating the conditions under which constancy occurs in everyday life, but it is not amenable to as much manipulation as an experimental situation worked out by Adhémar Gelb of the University of Frankfurt. In my laboratory at Swarthmore College some 15 years ago we undertook to explore with Gelb's setup some of the inconsistencies of the orthodox explanation of constancy.

We suspend a dark gray sample some distance from a light-colored wall and illuminate it with a projection lantern so placed that the bright spot formed where the beam hits the wall is concealed behind a door or curtain. With the room nearly dark, the dark gray sample appears brightly luminous, provided that it is perfectly flat and evenly illuminated so that no shiny high lights show. As the general illumination—and hence the illumination on the light wall behind the suspended sample—is raised, the luminous appearance of the sample disappears and it becomes a white surface. Remember that the sample is really dark gray; in this situation constancy is clearly absent. A further

increase in room illumination changes the appearance of the sample to a light gray. Obviously the wrong illumination is being taken into account! The light reflected by the dark sample is being evaluated in terms of the general illumination on the wall; the strong light from the projector is being ignored. The reason for this, proponents of the standard explanation would say, is that the strong light from the lantern is visible on only one object, the dark gray sample, the surround of which reflects only the dimmer general illumination; constancy would be restored if the light from the lantern showed in the surround. And so it is. When a piece of white cardboard, somewhat larger than the sample but small enough to fit into the beam, is hung behind the dark sample, the sample looks dark gray. The orthodox explanation is that the white cardboard surround makes it possible to take into account the effect of the lantern light on the intensity of the light reflected by the dark sample.

What happens when we vary the intensity of the lantern beam? With the gray sample alone intercepting the beam, every reduction in the intensity of the light causes a change in the apparent color of the sample, which can be altered in this manner all the way from white to dark gray. With constancy restored by the addition of the white cardboard, however, the same changes in light intensity hardly affect the color of the sample and its surround. The sample remains dark gray and the surround white, although the latter looks more or less strongly luminous as the lantern light is varied. This "luminousness" is a special aspect of neutral-color perception, as will be seen; in so far as the neutral colors as such are concerned, however, the combination of dark gray surface with white surround is resistant to changes in illumination.

It is difficult to see how this demonstration of constancy can be explained by any mechanism that takes the illumination into account. The amount of light the white cardboard reflects, after all, gives information about the intensity of the illumination only when the cardboard is correctly assumed to be white. But there is no cue for such an assumption. What if the cardboard were not white? As a matter of fact a surround of any other color fails to produce constancy, that is, to cause a dark gray sample to be perceived as dark gray. If, with the walls of the room dark, the white cardboard is replaced by a medium gray one, the surround again ap-

pears luminously white in the lantern beam, whereas the dark gray sample looks light gray. Although the color is now incorrectly perceived, the combination of sample and surround is still resistant to illumination changes. The intensity of the beam can be moved through a broad range and the sample remains light gray.

If taking illumination into account is not the explanation of constancy, what is? Some years ago Harry Helson, then at Bryn Mawr College, proposed an entirely different approach, invoking the mechanism of adaptation by which the eye adjusts itself to wide variations in the amount of light available. To account for the fact that constancy prevails when different illuminations are visible simultaneously, he suggested that incoming light intensities are evaluated in terms of a "weighted average" of stimulation in different parts of the retina, the light-sensitive screen at the back of the eye. It seems to me that there is implicit in this notion of regional adaptation an assumption of some sort of interaction of processes arising in different parts of the retina, and such interaction would appear to be a requirement in any explanation of constancy. Helson's explanation was advanced as part of a general theory of sensation that has been quite successful, and he did not describe a specific mechanism for interaction.

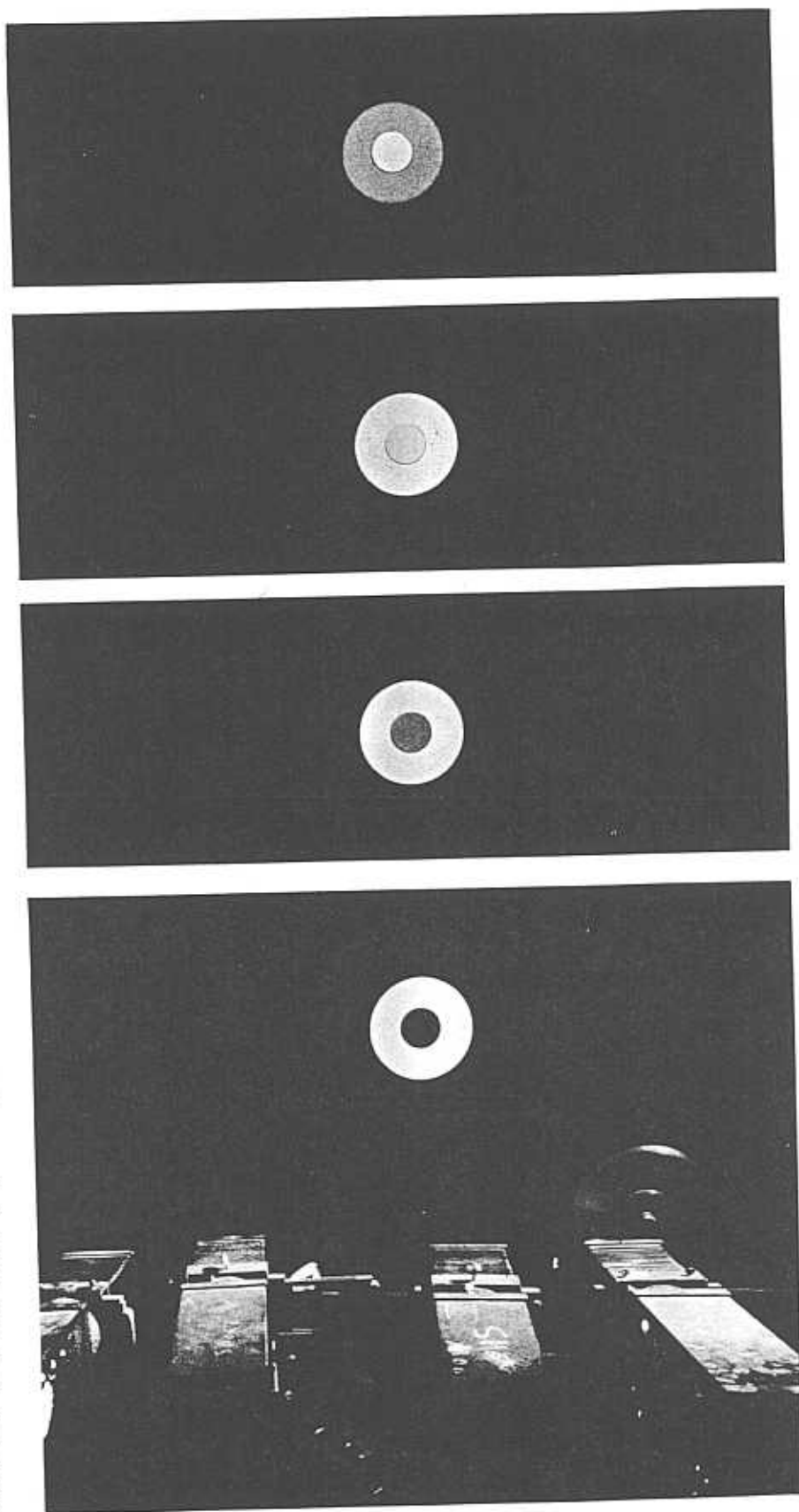
Speculating on the observations just described, in which the combination of gray sample and cardboard background proved resistant to changes in illumination, I wondered if a ratio effect might be at the heart of the matter. Since any neutral surface reflects a constant fraction of the available illumination, the light intensities reflected by two different surfaces under the same illumination should stand in a constant ratio no matter how the illumination is changed. If one could demonstrate that perceived neutral colors depend on the ratio between the light intensities reflected from adjacent regions, all the foregoing observations, and in fact neutral-color constancy in general, would be explained. The following experiments show that this is indeed the case.

The first experiment calls for a darkened room, a white screen and two identical slide projectors the light intensity of which can be altered by measured amounts. In an otherwise dark room one lantern projects a disk of light on the screen and the other lantern a ring of light that fits closely around the disk. The light intensity of the disk is

kept constant; variation of the intensity of the ring then changes the appearance of the disk through the entire range of neutral colors. When the ring intensity is half or a quarter that of the disk, the disk looks white. When the ring intensity is higher than that of the disk, the disk becomes gray. Its shade deepens from light to medium to dark gray as the ring light is made first twice as intense as and then four and eight times more intense than the light in the disk. When the relative intensity of the ring is raised still further, the disk even appears black. This experiment shows clearly that the neutral color of an area does not depend on the intensity of the reflected light as such, because with the intensity of the illumination of the disk held constant its color nevertheless ranges all the way from white to black as the intensity of its surround is increased. Obviously what matters is the relation of the intensity of the light reflected from the disk to the intensity of the light reflected from the surrounding ring.

Another experiment demonstrates that a particular gray is produced largely by a specific ratio between the intensity of the ring and that of the disk. A second pair of lanterns is added to project an identical ring-and-disk pattern on a second screen. If the ring and disk in each pattern are illuminated with the intensities in the same ratio but with the absolute intensity in one pattern reduced to, say, a third or a quarter of the intensity in the other, almost the same gray is perceived in both disks. Whenever the intensity of one of the disks is varied until the grays of the two disks appear to be truly equal, the disk intensities turn out to be almost equal fractions of the intensities in their respective rings.

The discovery that the various gray colors depend approximately on the ratio between light intensities stimulating adjacent regions of the retina goes a long way toward explaining neutral-color constancy in general. The ratio principle can account for the observed constancy in the Katz experiment, where a sample in shadow is compared with one in direct illumination. The combination of sample and background is resistant to differences in illumination because the ratio between the intensities reflected by sample and background is constant. It will be recalled, however, that constancy was not complete in the Katz experiment. A ring-and-disk demonstration explains this also. The ratio principle operates best only when the ring and disk are presented against

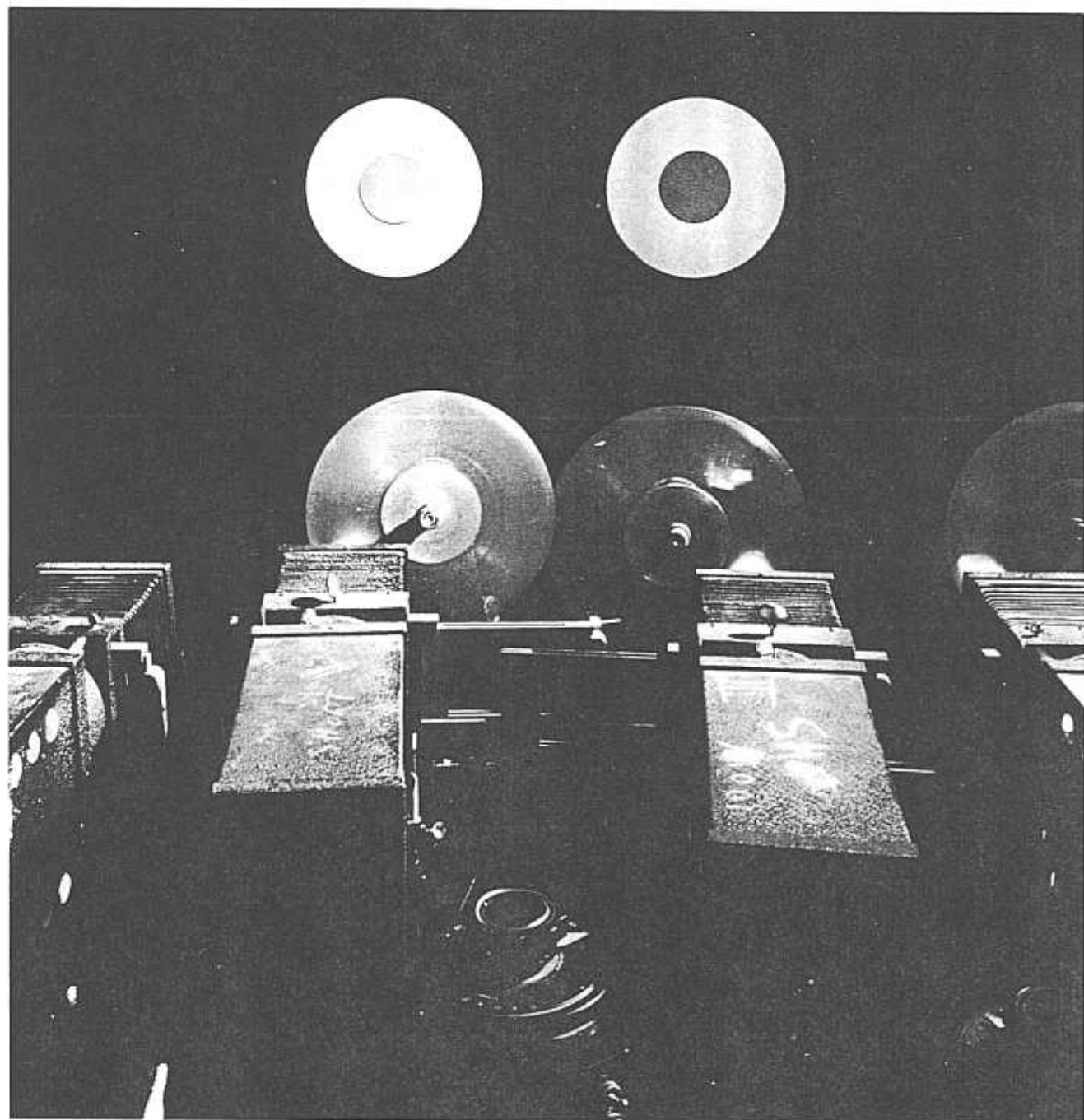


NEUTRAL-COLOR PERCEPTION depends largely on the ratio between two different light intensities in adjacent regions, as demonstrated with a ring-and-disk pattern projected by two lanterns in a dark room. In this experiment the light in the disk is kept constant but the ring light is increased, changing the appearance of the disk from white to dark gray. The ring-to-disk ratios are (top to bottom) one to three, two to one, four to one and eight to one. These photographs show how the ring and disk colors appear to an observer.

a dark background or when the ring is enlarged to fill the whole visual field. If, instead, the ring is surrounded by an area of still higher intensity, the disk assumes a darker color. And this is in essence what happens in the Katz setup: the gray sample and background in the shadow correspond to the disk and ring, and the portion of the background that remains under direct illumination corresponds to the outer region of still high-

er illumination that makes a disk appear darker. It is largely because the shaded region and the area under direct illumination are adjacent that constancy is incomplete. Were they widely separated, as they are in the presentation of two ring-and-disk patterns, much better constancy would result, because the ratio principle would then operate as nearly perfectly as it did in the projector experiments.

Although perception of illumination may not be very accurate and does not account for the constancy of neutral colors, it cannot be denied that people do perceive conditions of illumination. A room looks generally brighter near the window than it does far from the window; there is a bright area on the wall near a lighted table lamp and there are shadows on other walls; one side of the house across the street appears brightly



RATIO PRINCIPLE is confirmed by projecting a second pattern from two more projectors. The ratio between ring and disk light intensities is made the same in both patterns but the absolute intensities in the pattern at the left are four times greater than

those at the right. In spite of the variation in absolute intensity, the grays perceived in the two disks look remarkably similar to an observer. The photograph, however, approximately reproduces the true light intensities rather than the apparent disk colors.

illuminated by the sun. How, in view of the ratio principle, is one to account for the fact that the shadow on the gray wall does not look exactly like a darker gray or black but has a somewhat translucent appearance; that the wall near the lamp does not seem to be lighter in color but merely looks brighter and less opaque; that the sunlit wall of the house looks outright luminous? All of these examples have one thing in common: the typical quality of a surface of neutral color is either completely replaced by a luminous appearance or is modified in the direction of what can be considered a partially luminous quality. The two-projector experiment, as already noted, also produces examples of this luminousness and of a translucent quality

in the grays that is the low-intensity counterpart of the same effect.

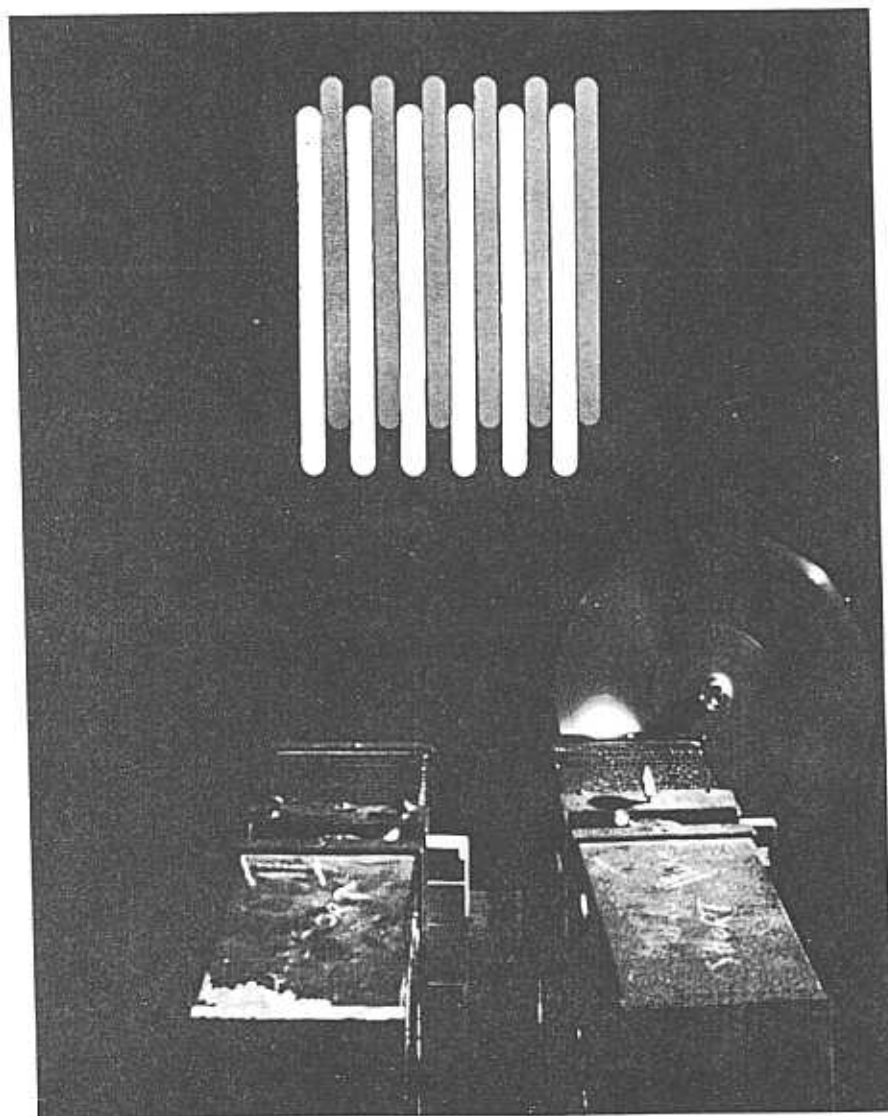
When the intensity of the light reflected from the disk is two to four times higher than the intensity of that reflected from the ring, the disk looks white; when the intensity of the disk is lower than that of the ring, the disk looks gray or black depending on the ratio between the two intensities. If the intensities of ring and disk are reversed, however, the appearance of the ring is very different from that of the disk under corresponding conditions. Under illumination of the higher of the two intensities, the ring appears not white but plainly luminous, like the glass globe of a not too bright lamp. Under illumination of the low-

er intensity the ring does look gray, but the gray has a peculiar quality. It lacks the opaqueness of an ordinary surface; it seems rather to be somewhat translucent, as if there were a light source behind it. As a matter of fact it resembles an extended shadow, which also lacks the opaqueness of a dark surface color, although to a lesser degree. With the ring eliminated altogether, the dark region surrounding the disk does not look like an opaque black surface but like a dark expanse. The distinction between the two kinds of darkness is pointed up vividly when the disk is eliminated and a ring of light is projected alone on a dark field. The area inside the ring has a black surface color quite different from the dark expanse outside the ring.

Several factors seem to account for the sensation of luminosity. The larger of two contrasting areas, in the first place, tends to appear luminous. In our experiments the ring was usually larger than the disk. With the ring reduced in width so that its area is smaller than that of the disk, the appearance of luminosity and translucence transfers to the disk. The degree of contact between two surfaces reflecting different light intensities also plays a part in this effect. Surrounded completely by the ring, the disk tends to look more like an opaque surface. The ring, which tends to assume the luminous quality, is in contact with the disk on one side only and is bordered on its outer perimeter by the darkness of the room, from which there is minimum stimulation. Lack of contact also explains the luminousness or translucence observed when the disk or the ring is presented alone.

To isolate the effect of difference in contact we have projected two sets of bars, one from each lantern, so that bars of high and low intensity alternate in the pattern on the screen. The two outside bars, one white and one gray, appear somewhat luminous, whereas all the other bars show opaque colors. Since the areas of each bar and of each intensity are exactly equal, the luminous look can only be attributed to the diminished contact of the outer bars with areas of different intensities. A special case of reduced contact occurs when an intensity gradient replaces the sharp border between two areas of different intensities. Such gradients appear in the penumbrae of shadows, where the grays assume the quality of translucence that belies the opacity of the surface under inspection.

Regardless of size or degree of con-

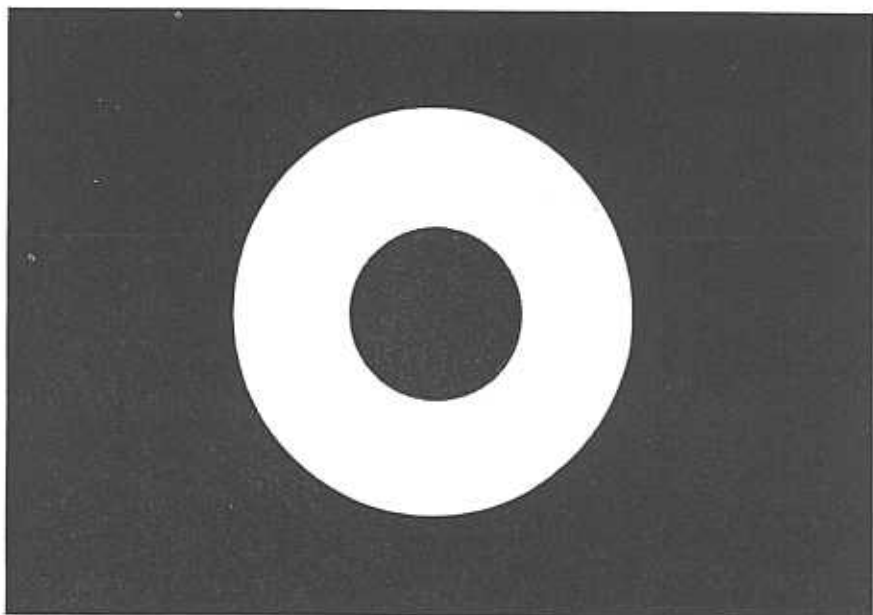
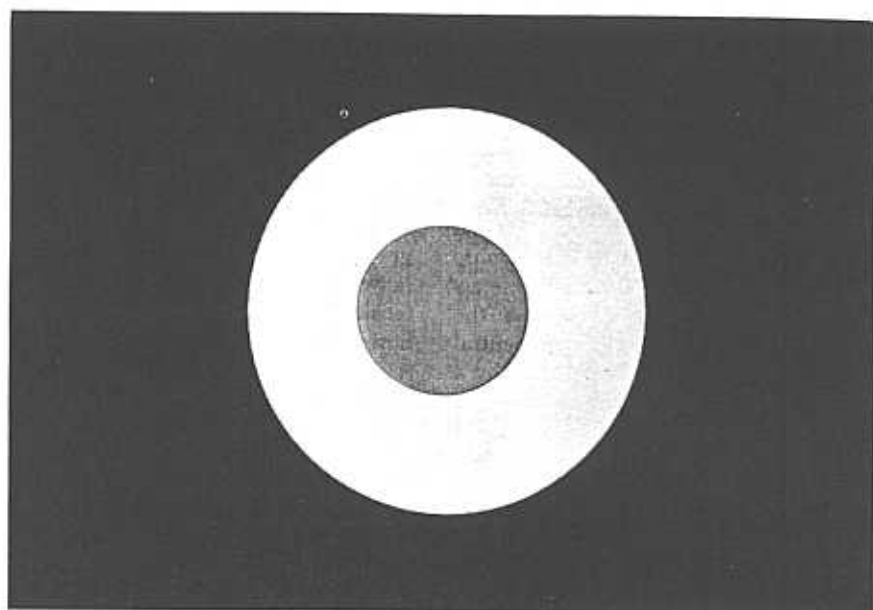


LUMINOUS QUALITY is produced by a reduction in the degree of contact with an area of contrasting light intensity. In this pattern of bars of alternating high and low intensity, the two outside bars look somewhat luminous to an observer (the effect is not apparent in a photograph) because they have only half as much contact with contrasting bars.

tact, when the intensity difference becomes greater than about four to one, the area of higher intensity becomes somewhat luminous as well as white; with very large differences it loses all whiteness. An illuminated disk in an otherwise dark field never looks white or gray; depending on its intensity, it is brightly or dimly luminous. The most familiar illustration of this laboratory finding is the contrast between the appearance of the moon by day and by night. In a bright blue sky the moon looks white. As the setting of the sun reduces the intensity of the blue sky the moon's light becomes relatively more intense and the moon appears more and more luminous, even though the intensity of the light arriving from the direction of the moon certainly does not increase.

It can be concluded, therefore, that a region reflecting the higher of two light intensities will appear white or luminous, whereas an adjacent region of lower intensity will appear gray or black. Every change of the intensity ratio causes a change in the color of the area of lesser intensity along the scale of grays. As for the area of higher intensity, it appears white when the intensity ratio is small and becomes luminously white and finally luminous as the ratio is increased. If the contact between surfaces of different intensities is reduced, neutral colors become less dense and opaque and even somewhat luminous. The same effect is seen in a region that is larger than an adjacent one of different intensity.

It seems to me that these facts can be explained by considering that stimulation with light gives rise to two different perceptual processes. One process causes luminousness and the other produces the various opaque colors. The first process is directly dependent on intensity of stimulation and the state of adaptation of the eye. The second is an interaction process: an area of the retina that receives a higher intensity of stimulation induces a sensation of gray or black in a neighboring region of lower intensity, with the particular color roughly dependent on the ratio of the two intensities; conversely, the region stimulated at a lower intensity induces a white color in the region of higher intensity. If the intensity ratio is too high, however, if the relative size of the inducing surface is too small or if the contact between two regions of different intensities is too small, the interaction process may give way to the process that gives rise to the sensation of luminosity, or the sensation of color and luminosity may be experi-



CHROMATIC COLORS also vary in lightness depending on the intensity of the illumination in an adjacent region. The experiment simulated here shows how the appearance of a disk of orange light changes with the intensity of a neutral surround. In this case increasing the intensity of the ring changes the apparent color of the disk to brown.

enced simultaneously.

The processes of neutral-color perception have their counterparts in the perception of chromatic colors. This is not surprising; the neutral colors are continuous with the chromatic colors: for any sample of a greatly desaturated chromatic color a closely similar gray can be found. A final experiment with the two projectors demonstrates that the lightness of chromatic colors depends on a relation between the intensities of stimulation in neighboring regions. When a disk of chromatic light is sur-

rounded by a ring of white light, variation in the intensity of the latter changes the lightness of the chromatic color in the disk. In this way a bright pink, for example, can be changed to a dark magenta. The same experiment performed with a yellow or orange disk yields a surprising result: surrounding the disk with a ring of high-intensity white light transforms the disk into a deep brown. This serves to demonstrate that brown is a dark shade of yellow or orange. It also dramatizes the point that the shades and tints of chromatic colors, as well as the neutral colors, are the re-

sult of an interaction process.

Even the luminous appearance that results from stimulation with light from a neutral surface has its counterpart in the sensation of chromatic colors. For many years psychologists have distinguished a number of "modes of appearance" of chromatic colors, including surface colors, expanse colors and aperture colors. Surface colors are the opaque colors of objects, the hued counterparts of the neutral surface colors. Expanse colors, of which the clear blue sky is a good example, occur in extended homogeneous regions and lack the density and opaqueness of surface colors. That is, expanse colors have a luminous appearance, which may be caused by a relatively high intensity of stimulation or because they are greatly extended in relation to an adjacent region of different intensity. Aperture colors are observed

when one looks through a hole in a screen at a chromatic surface some distance beyond the screen. Under these conditions the surface is transformed into a seemingly transparent chromatic film stretched across the hole.

The aperture mode has been attributed to the peculiarities of the laboratory arrangement in which it is usually observed. It can be shown, however, that this effect too is a product of specific ratios of stimulation intensities. The "transparent film" appears only when the intensity of the light reflected from the chromatic surface seen through the hole is high in relation to that of the light reflected from the screen. Raising the illumination on the screen transforms the film into a surface color, so that the hole comes to look like a piece of colored paper attached to the screen.

Such a change can be observed easily

out of doors on a clear morning. Cut a small hole in a large sheet of white cardboard. Hold the sheet up so that the sky is visible through the hole. The sky will appear in the hole as a blue transparent film. Now turn until the white cardboard reflects the direct light of the sun. When the cardboard is brightly illuminated, the hole seems to be replaced by an opaque bluish-gray patch, notable for its lack of saturation. This transformation of the strongly saturated expanse color of the sky into a surface color of medium lightness by the provision of a relatively large surface of contrastingly high light-intensity shows how desaturated the blue of the sky really is. It suggests that the sky looks very blue not only because the blue wavelengths of sunlight are scattered by the atmosphere but also—and perhaps largely—because the sky is so bright.