The Colors of Things

Color "illusions" devised (for the first time) on the display screen of a computer are evidence that color is not perceived just by sensing the light from individual surfaces in a scene

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Color, like beauty, is in the eye of the beholder. It is a private experience and, like any other experience, is not accessible to measure. There is, however, a common belief that color, unlike beauty, is determined directly by physical cause: the spectrum of the light that falls on the eye. In particular the eye is taken to resemble a color television camera, which measures how much energy there is in the long wavelengths (red), middle wavelengths (green) and short wavelengths (blue) of the light at each point in an image. The eye, like the camera, has three types of color sensors, and so it is thought the color at every point is perceived by sensing the redness, greenness and blueness of that point.

This general belief is the impetus for many of the color "illusions" devised by investigators who study visual perception. The underlying notion in such displays is that you ought to see one color but in fact see another. Usually the "illusions" are taken to show the fallibility of the senses: to show the eye does not really work as well as it should. An alternative view is that the conventional notions about color vision are quite wrong if they are so easily and consistently violated. The "illusions" do not reveal defects. They yield insights into the unconventional design of color vision.

The unconventional notion we shall champion in this article—and test in a sequence of illustrations—is that the perceived colors of things in the visual world do not depend slavishly on the light from each object, sensed independently of all the other things in the world, but on a comparison of the lights from an object and its surroundings. That assertion seems mysterious. After all, the colors of objects are perceived as an intrinsic property of their surfaces. A red rose in daylight seems absolutely red, not red in relation to what is around it. But this perception of intrinsic redness does not signify that the redness is given only by the sense data in the image of the rose alone. We shall be concerned not with accounting for how perception seems to the perceiver but with the process applied to the sense data so that perception is possible.

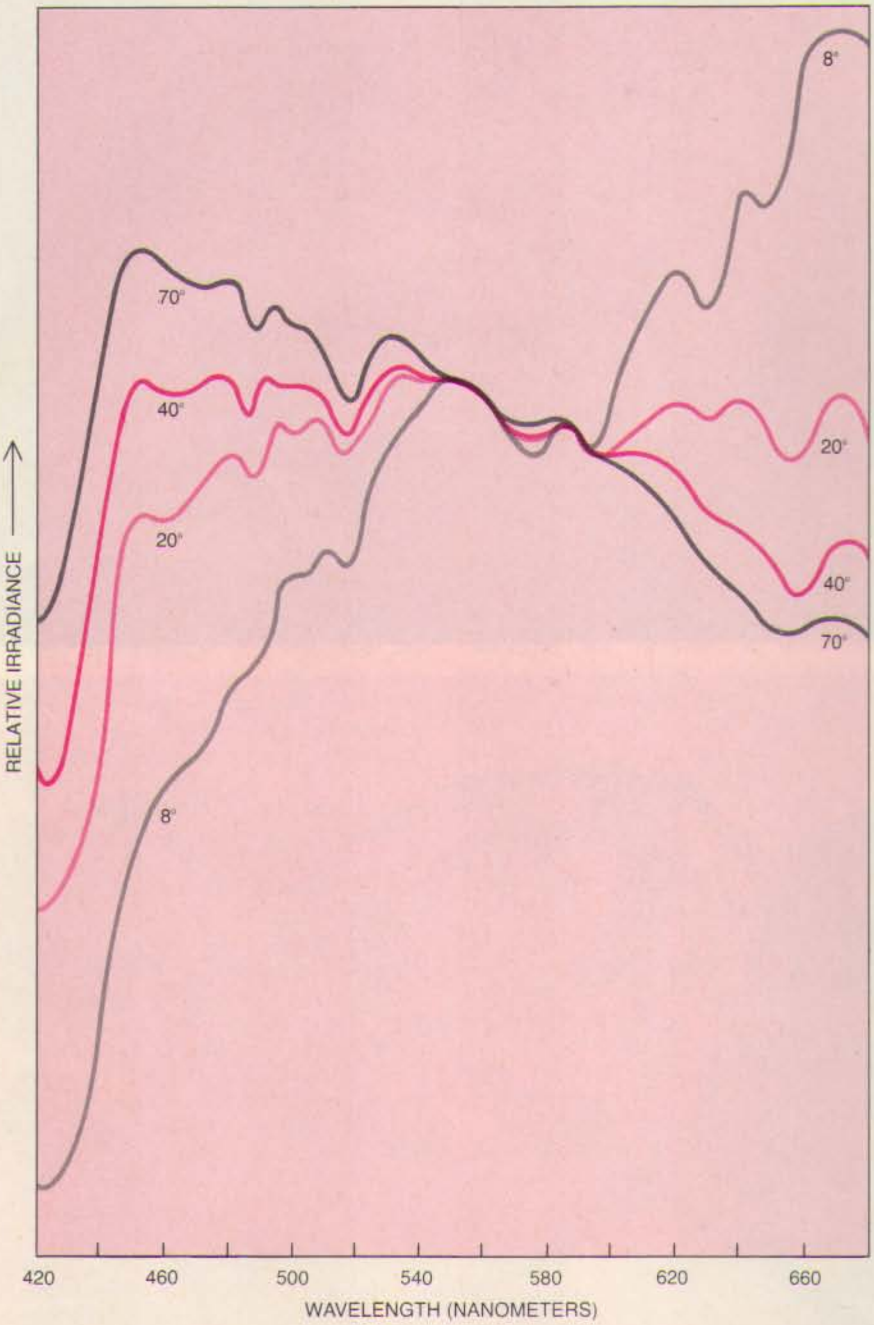
The key that something is wrong with the conventional notions about the colors of things is in fact a color "illusion"—the most universal "illusion," an "illusion" so much in one's daily experience that it escapes notice. It is the color constancy of objects in daylight. Outdoor illumination is not fixed; it changes not only in brightness, from dawn to high noon to twilight, but also in its spectrum. At dawn the light is rosy. In the afternoon it is distinctly yellow. The north light preferred by artists is the blue of the sky when the sun is excluded. The diffuse light under a leafy arbor looks fairly green. Yet under the various forms of daylight a white sheet of paper is always seen as white. In fact all the surfaces one sees outdoors stay quite constant in color however the daylight varies.

Today color constancy, if it is mentioned at all, is treated by a skeptical footnote in textbooks on vision. The skepticism is not hard to understand. Since many of us virtually live our lives under artificial lighting, we have become inured to the experience that faces and cosmetics, for example, change color between incandescent and fluorescent lighting. Yet the skepticism is wrong. Investigators of a century ago knew that color constancy poses a serious problem for efforts to understand perception. The constancy is so reliable that one routinely compares by memory the face color and lip color of someone who now stands under one form of daylight with the colors seen an hour ago, a day ago, a week ago, and under another form of daylight, and thus detects changes due to blushing or paling or signifying disease such as jaundice (which turns the skin yellow) or anoxia (which turns it blue). Such changes are much smaller than the possible changes in daylight color. It is as if, in the words of the 19th-century physiologist Hermann von Helmholtz, we "discount the illuminant" when we perceive color.

Helmholtz supposed that we know, by memory or intention, what colors we ought to see, and so adjust our perceptions to discount the lighting. But he was uncomfortable with the idea, and rightly so. It calls for a miracle, since one cannot tell, by means of any imaginable sense organ, what light plays on anything except that organ. That is, you cannot tell what light illuminates a surface; you only receive a part of that light—the part the surface reflects to your eye. How then can you "discount the illuminant"?

COLORED SHADOWS constitute an "illusion" that offers insight into the unconventional workings of color perception. In both photographs a bust of the 19th-century explorer and scientist Alexander von Humboldt has been placed in front of a white background. The bust is illuminated from one side by a beam of white light and from the other side by a beam of tinted light. The bust faces the tinted beam; hence the shadow behind the back of the head contains only white light. It does not look colorless, however: it has the color complementary to the opposite, tinted shadow. Thus the shadow behind the back of the head in the top picture looks "warmer" than the corresponding shadow in the bottom picture. Masking the shadows' surroundings will show that the shadows are virtually identical. The "illusion" hints that color perception relies on comparisons across boundaries in an image.

Our attempt to answer that question must take account of a difficulty that bedevils all efforts to talk about color. There are really two distinct types of explanation of color vision. The first type has to do with how information from a visual image is converted into sense data. That is, the explanation concerns itself with how the cones, the color sensors of the eye, react to light. In each cone the arrival of light bleaches a light-sensitive pigment; thus the explanation concerns itself with the rates of the pigment-bleaching events caused by arriving photons, or particles of light.



VARIETIES OF DAYLIGHT differ markedly from one another in their physical properties, notably their spectrum, yet the perceived colors of objects in daylight are remarkably constant in spite of the changing illumination. The phenomenon is called color constancy. The four curves chart the spectrum of the diffuse illumination at ground level at four times of day, when the sun is at various angular distances between the horizon (0 degrees) and the zenith (90 degrees). The curve for the sun at eight degrees was measured about half an hour before sunset. The peak in the spectrum of diffuse daylight then occurs at roughly 660 nanometers, or deep in the red part of the spectrum. Hours earlier, when the sun is high in the sky, at 70 degrees, the peak is at wavelengths some 200 nanometers shorter, or well into the blue part of the spectrum. The four spectra were first published by S. T. Henderson.

The experimental analyses that reveal the laws of this transduction start with Newton. The strategy is to have human subjects act as what are called null measuring devices. The subjects adjust a reference light (they can, for example, adjust the brightnesses of three colored lights that combine to produce a spot of light) until the boundary between the reference and an adjacent test light vanishes and the reference and the test light can no longer be distinguished. The experiments establish that certain lights bleach the visual pigments identically. In other words, the experiments serve only to build up a description of the pigmentary responses. They are independent of anything that may happen to the sense data after the cones produce them.

The second type of explanation is very different. It lies beyond the domain of measurable quantities such as the brightnesses of test lights. Instead it takes as its realm the perception of color. Everything known about the apparatus of the eye and everything inferred about the brain from physiology and psychology shows that the perceiver is directly aware not of raw sense data but only of the consequences of a process applied to the data. The appropriate strategy in devising an explanation of color perception is therefore to take the laws of data acquisition as given (the first type of theory addresses that matter) and search out the rules for dealing with the data.

We think it facilitates such a search to adopt the attitude of the engineer, who is concerned not so much with analyzing the world as with designing a system that fulfills a particular purpose. (The engineer always "builds to specifications.") The art is to conceive of the purpose of color vision and then design a system to realize it.

Color vision, as a useful faculty, evolved in a primeval world in which light from the sun—scattered, refracted and reflected—was the chief illuminant. The things it lighted were mostly solid, opaque, nonmetallic objects, which reflected the light according to their material composition and the roughness, irregularities and nonplanarities of their surfaces. The objects were distributed independently over the earth. Any image of such a world is a two-dimensional map of a determined chaos: a bounded region in the image is almost always bounded by many other regions, and the change in light across one of the boundary segments has little predictive value for the change across any other boundary segment. In sum, three conditions—daylight, varied reflectances and a diversity of arrangements—are the constraints under which color vision evolved.

Imagine the purpose of color as an aid to seeing. Color vision improves the ability to tell surfaces apart in a memorable way, so that nourishment, threats and so on can be learned and reliably recognized. Since color vision supports many more distinctions than monochromatic black-and-white vision, there is surely an advantage to seeing in color. Yet unreliable distinctions are useless. Indeed, they are a hindrance. They are busyness without meaning and so are equivalent to noise. This gives value to color constancy. The ability to recognize things would be lessened if their color changed simply because of a change in the illumination.

What then, in terms of color, will serve as a memorable quality of a surface, a quality both intrinsic to the surface and independent of the accidental circumstance of what form of sunlight plays on the surface? The only quality that meets these conditions is reflectance: the ability of the surface to reflect light of each given wavelength. As it is ordinarily defined, the reflectance is unknowable. It is the ratio of the light incident on a surface to the light the surface reflects, and (as Helmholtz ruefully knew) the eye has access only to the latter. Hence the notion of employing reflectances as a basis for color vision seems absurd. It is absurd, however, only if one accepts as dogma that the color of a surface depends on the light from that surface alone.

There are other possible tactics. The most straightforward one replaces measures of the light reflected from individual surfaces with comparisons of the lights reflected from pairs of adjacent surfaces. If the surfaces are under the same illumination, the comparison is independent of the incident light. As a result the comparison of the reflected lights becomes equivalent to a comparison of the reflectances (which are unknowable individually). We have arrived, then, at the hypothesis that perceived color is a quality of the reflectance of a surface compared with the reflectances of other surfaces. It is a testable idea; it suggests, for example, that the perception of a stable color at a given point in an image requires that the regions near the point be sufficiently diverse. It is an idea we shall now examine by means of a sequence of color "illusions." They are patterned after displays devised by Edwin H. Land, who founded the Po-

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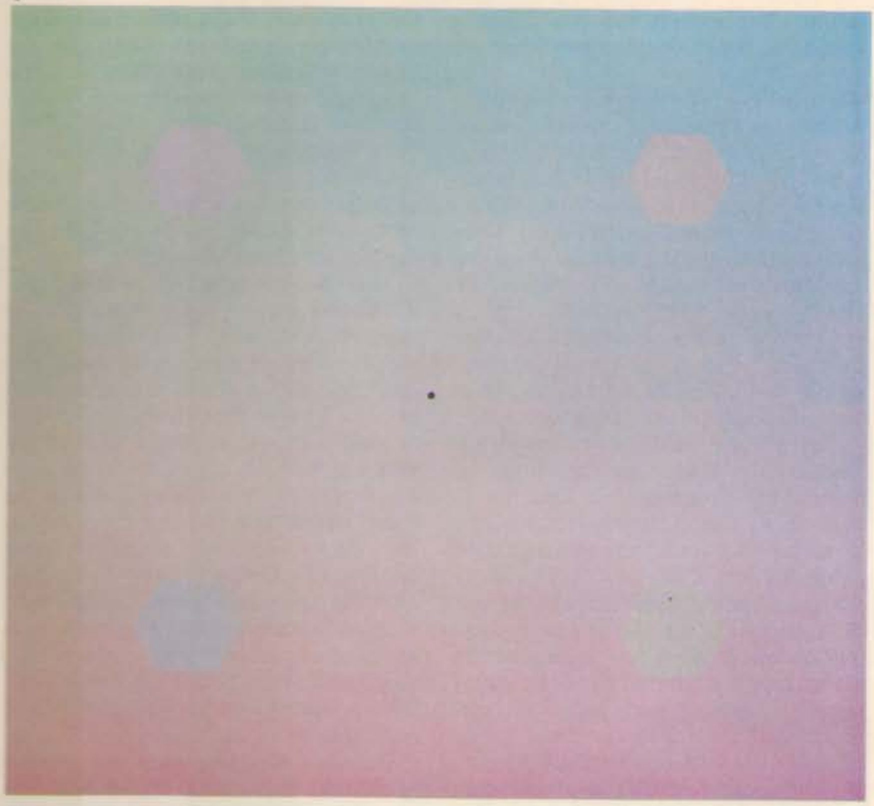

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"ILLUSIONS" IN AN ARRAY of colored hexagons were photographed on the screen of a computer. Each hexagon in the first display also appears in the second. In the first display, however, the hexagons are ordered chromatically; in the second one their positions have been randomized. The randomization makes the range of colors look more vivid. Five hexagons have the same chromaticity (the same spectrum) and retain their position from one display to the other. In the first display they seem to have somewhat different colors; in the second one the color (a fairly neutral gray) is recognizably the same for all five of them.

laroid Corporation and has devoted himself to the study of color vision.

In this era of personal computers with color display screens, color manipulation is easy; indeed, the "illusions" we shall show can be had on ordinary television screens. The display screen was photographed (at the Massachusetts Institute of Technology) by Bradford Howland and Denise D. Denton, who used standard camera equipment and a standard film. The only difficulties arose because photographs published in a magazine have to go through the printing process.

There were really two problems. The first is that color printing has a dynamic range of less than 10 to one across the spectrum. That is, the brightest patches of any given printed color are less than 10 times brighter than the dimmest patches of that color. Even the black ink in which these words are printed has a reflectivity about a tenth of that of the white paper itself. In contrast, transparencies (color "slides") enjoy a dynamic range of well over 100 to one. Thus printing sharply compresses the vividness of an image in a way that a color transparency does not. In order to ensure that the images we photographed would not be much corrupted by such compression, we limited the dynamic range of the color brightness to three to one, or less. The pictures are printed versions of displays that could safely be made more vivid if they were intended to be projected rather than printed.

The second problem is that standard color printing uses three colored inks (magenta, cyan and yellow) quite different in chromaticity from the red, blue and green of the computer-display-screen phosphors. In consequence the printing press cannot lay down greens of the same brightness and saturation as the ones given by the computer display screen, even within the limited dynamic range we have chosen. (To get vivid greens in printed advertisements, manufacturers of menthol cigarettes often pay extra to have an additional ink, a green one, employed in the printing.) These limitations were taken into account in the construction of the figures.

Examine the two displays on the preceding page. They are identical in their components. Each display is an array of hexagonal patches of color, and every hexagon that appears in one display appears somewhere in the other. Every hexagon has a "chromatic signature" defined by three numbers, one giving the intensity of the red pixels (the individual points of brightness on the computer display screen), the second that of the green pixels and the third that of the blue pixels. The only thing that differs from one display to the other is the positions of the hexagons with respect to one another: their addresses on the screen.

In the first display the hexagons are ordered according to their three components. Red increases in intensity from top to bottom of the display, green from bottom to top and blue from left to right. The steps in intensity from each hexagon to the next have been arranged to be somewhat stronger than just visible. The second display is a very different image. The range of colors seems wider and more vivid. Yet the only difference is that the colored hexagons have been shuffled—given random addresses rather than ordered ones.

It is instructive to try to tell the change of a given colored hexagon's address from one display to the other. For a hexagon at the boundary of the first display the new, randomly set position in the second display is relatively easy to find. But we doubt that your eyes will be of much help to you in discovering most of the new positions unless individual hexagons are masked off from the others.

Five of the hexagons in each display are special in two respects. First, their addresses are constant. In both the first display and the second they are the central hexagon and four outlying hexagons, one near each corner of the display. Second, the five hexagons are identical in chromatic signature. The rest all differ in their characteristic triple of numbers.

Try to compare the five. In the first display they should seem to be of differing colors, in spite of the narrow dynamic range of the illustration. (The effect would be stronger if we could increase the dynamic range.) But if, at ordinary reading distance (about 16 inches), you fix your gaze on any one of them, it should turn indeterminate in color.

It is unlikely that you can make out the central hexagon. It is marked with a small dot in its center. If you fix your gaze on the dot (closing one eye), the colors of the four outlying hexagons should seem strong at first, but within a few seconds the hexagons

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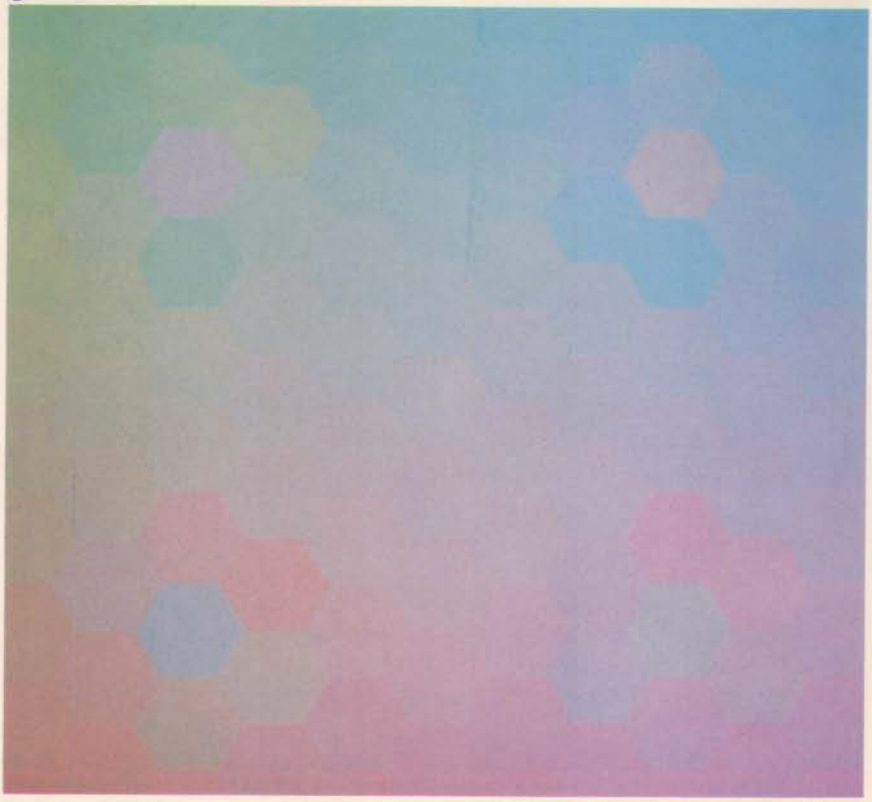

REARRANGING THE RING of colored hexagons that border each gray hexagon does much to abolish the wandering colors of the gray hexagons and make them look reliably gray. In other words, it goes far toward establishing color constancy. The rearranged rings represent the only change from the first display; the rest of the colored hexagons retain their chromatic order. The display therefore suggests that color perception relies in particular on local comparisons across the boundaries between patches of color in a visual image.

should vanish. Indeed, the entire picture should seem to become quite featureless except at its perimeter: its boundary with the white page.

Again the second display is quite different. The five hexagons should look uniformly gray, although they occupy the same positions and have the same chromatic signature they had in the first display. If you fix your gaze on any one of the five, you should find that its color remains reliably gray. Furthermore, fixing your gaze on the central dot should not bring on a general deterioration of the image, as it did for the first display.

The results of these explorations are readily summarized. The randomizing of the colored hexagons surrounding the five gray hexagons somehow leads to more vivid color perception and at the same time stabilizes the gray hexagons. Conversely, the ordering of the colored hexagons lessens the vividness of their colors and makes the gray hexagons wander in color: it saps their color constancy.

In the third display, shown on the opposite page, we have modified the scheme of the first display only in the immediate vicinity of the four outlying gray hexagons. In particular, the ring of hexagons around each gray hexagon has been rearranged: the hexagons that bordered a gray hexagon in the first display still border it in the third, but their annular order has been changed. The averages of the intensities of the red, the green and the blue pixels immediately around a gray hexagon therefore remain as they were. Yet now the gray hexagons do not differ much in their color.

The fourth display, on this page, is even more faithful to the scheme of the first. Four outer hexagons bounding the outlying four gray hexagons have been exchanged diagonally. Otherwise nothing is altered. Yet again the gray hexagons no longer differ much in their color.

In the fifth and sixth displays, shown on the next page, the phenomena are much as they were in the first and second displays. The difference is that the computer program that generates the images has been altered so that the chromatic signatures are specified in terms of magenta, cyan and yellow, the pigments used in color printing. (The computer display screen still glows in its usual red, blue and green, but the proportions of these glows are adjusted to give combinations that mimic the printing inks.) The color "illusions" still hold, although, as one would expect, the seen colors differ from the ones in the first display.

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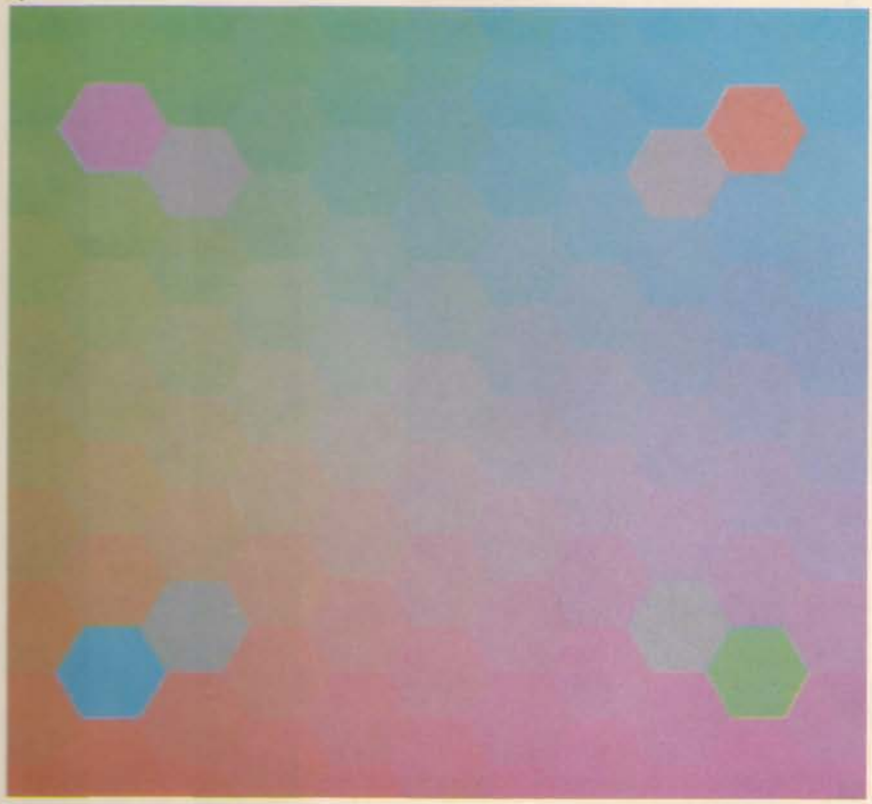

DIAGONAL EXCHANGE of colored hexagons also goes far toward making the gray hexagons look reliably gray. Here a single colored hexagon bordering each gray hexagon has been switched diagonally with its counterpart across the illustration; in all other respects the scheme of the first display is maintained. The exchange shows that the presence of a small area of marked spectral dissimilarity is sufficient impetus for color constancy.

We have one more "illusion" to show. The obverse of color constancy is the phenomenon called colored shadows. Its most familiar form can be seen on page 85, where we display two photographs of a real scene: a bust of the 19th-century scientist Alexander von Humboldt placed in front of a white background. In each photograph the bust is illuminated from one side by a tinted light and from the other side by a white light. It is hard to tell which light is which. One of the shadows in each photograph has the color of the tinted beam. (The bust has blocked off the white beam.) Yet the other shadow (where the tinted beam is blocked off) does not look colorless; it has the color complementary to the first shadow. The effect is particularly striking in patches of shadow on the bust itself. (In the illustration the tinted lights are to the right. The beams were adjusted to limit the dynamic range. A more florid effect can be had with projectors and transparencies.)

Why are colored shadows the obverse of color constancy? In both phenomena the color attributed to a light is different from what it "really is"—different from what the physical properties of the light would lead one to predict. In colored shadows the identical spectral distribution (that is, the same physical stimulus) has different colors. In color constancy different distributions have the same color.

In essence, then, the perceived colors of the five gray hexagons in the first display constitute a demonstration of colored shadows. Imagine that you could adjust the reflectance of each of the four outlying gray hexagons in the display so that they would all appear to be the same color as the central hexagon (the one with the dot). The four adjustments would be different. You would have turned colored shadows (the same stimulus looking different) into a semblance of color constancy (different stimuli looking the same). If the remaining hexagons were then shuffled, as they are in the second display, the five hexagons would have distinctly different colors among themselves.

Plainly the processing of color information from sense data does not give a slavish one-to-one correspon-

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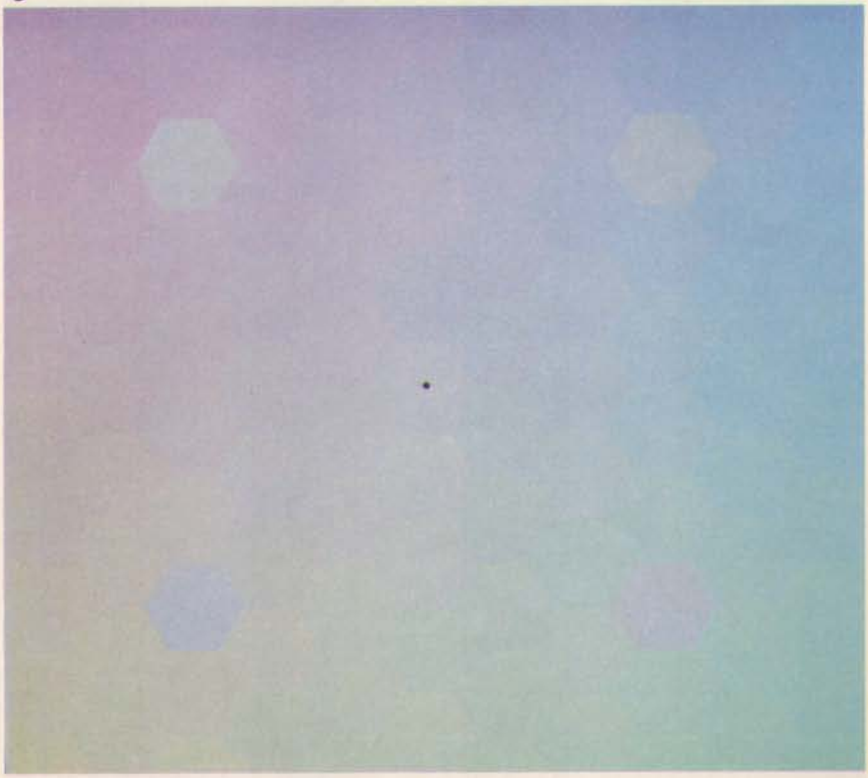

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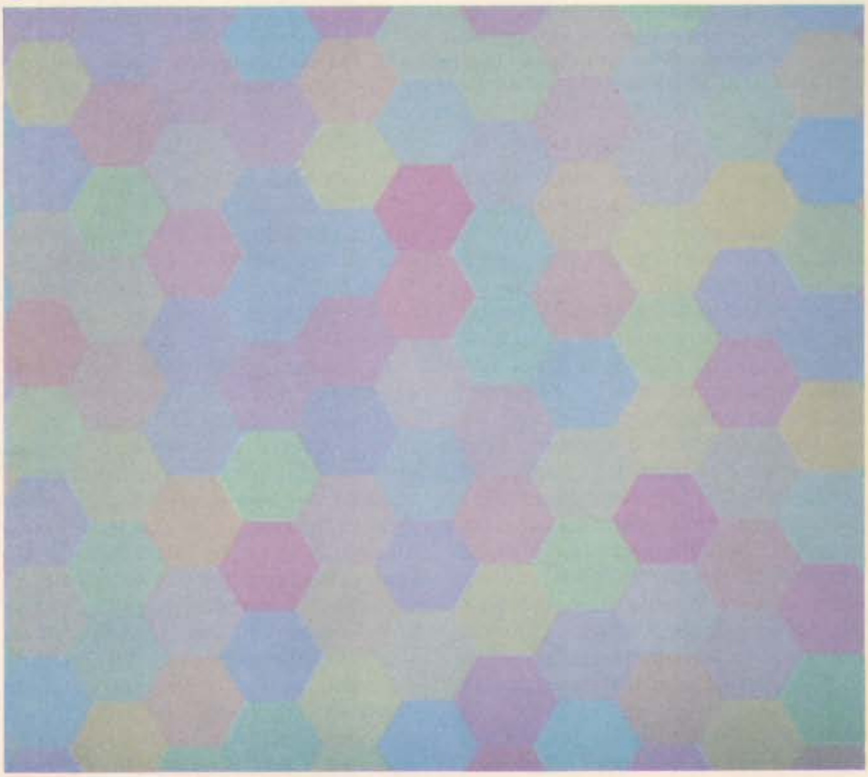

THE SAME "ILLUSIONS" as the ones in the first two displays are shown here for colored hexagons whose chromaticities have been adjusted to resemble combinations of the inks employed in color printing. That is, the hexagons vary in steps of brightness for cyan (a greenish blue), magenta (a purplish red) and yellow. Again the five gray hexagons in the display seem to have different colors when they are surrounded by ordered chromaticities, and they are seen to be the same when their surroundings are randomized. As one would expect, the perceived colors of the gray hexagons differ from the ones in the first display.

dence of perceived color to the spectrum of light. There is no such correspondence in one's daily outdoor experience, which is of color constancies and colored shadows everywhere. And so the rules for color processing must be different in kind from the laws that govern the responses of the visual pigments to light.

Some hints at the nature of the rules are suggested by the displays. The first hint is that colors are determined at boundaries and vertexes (where boundaries meet). Those are the only places in the pictures where the chromatic data change, so that ratios of reflectances can be taken. In this regard the first display is particularly instructive. Again, fix your gaze (with one eye closed) on the central dot in the picture. Observe how the four outlying hexagons vanish after a few seconds, then reappear, then vanish. With a little attention to detail, you should discover that the reappearance always accompanies a movement of the eye, so that after a little practice you can actually control the vanishing and reappearance.

This is a crude example of the phenomenon of stabilized images on the retina. It has been known since the 19th century that if an image is held steady on the retina, it vanishes, to be replaced by a peculiar feeling of blindness called the "empty field." The vanishing is due mainly to the fact that each receptor (each cone) in the eye adapts, or adjusts itself, to the light on it. Receptors are designed to signal to the nervous system only change, not a steady state. Vision is good as long as the eye moves about. When the eye rests, vision deteriorates. This confirms in no uncertain way that the boundary and vertex information is crucial for seeing, just as we inferred from the phenomenon of color constancy. The eye must move so that individual receptors can experience boundary crossings.

A second point is that the color of an area depends not only on the surroundings of the area but also on the running history of the region of the retina on which the area's image falls. That is, a set of receptors exposed to many different lights in succession will give a signal for any specific presentation of light that is different from the signal they will give if their history of exposures is an impoverished one. This conclusion too derives from the first display. Recall that if you fix your gaze on any of the four outlying hexagons, it rapidly becomes indeterminate in color. On the other hand, if you observe the picture cursively, letting your gaze wander about it, the impression of four differently colored hexagons remains.

The phenomenon of stabilized images suggests the explanation. Since a stabilized image vanishes, the strategy of looking fixedly at any surface in order to determine its color is unavailing. But since the receptors do not adapt instantaneously (modern apparatus shows that an image, however bright and contrasty, vanishes in about two seconds), the ordinary jiggle of the gaze gives abundant and varied information to the individual cones.

The second display and the ones that follow it teach the same lessons. They show that as the surroundings of an area become more varied, the color of the area becomes more definite and also more stable over time. Moreover, the color becomes more reliably a correlate of the area's reflectance. In the real world, diversity is the rule. There is rarely an orderly display of the kind shown in the first image—except in the patterns that give some animals protective coloration. This natural diversity, and the continual change of the direction of the gaze, ensures that the spatial surroundings of an area and the temporal history of the exposure of cones to light are as variegated as the engineer of a color-vision system could wish.

We turn, then, to some of the concerns of an engineer who undertakes to design a color-vision system. One of the most useful operations in any sensing system, natural or artificial, is a running normalization. In psychology it is called adaptation; in engineering it is automatic gain control. The idea is to adjust the sensitivity of the system to the average level of input so that all changes are made to lie in the same limited dynamic range. This is done by taking a running average of the input and using it to set the gain, or amplification factor. Imagine, for instance, a camera lens that darkens in bright light, grows clear in dim light, and does it so well that photographs taken with the same exposure time at bright noon and at twilight have the same quality.

The strategy of automatic gain control, applied to cone sensitivity, might take the following form. Call the intensity of the light currently falling on a cone L. The running history of arriving light is designated A. The latter is an average of the intensities of lights that recently fell on the cone and is adjusted so that the effect of a light diminishes with its distance into the past. Helmholtz called it "dark light."

Examine the difference between the light and the dark light, divided by the sum of the two (that is, the ratio of $L - A$ to $L + A$). It achieves automatic gain control. Under steady light, such that A (the dark light) is the same as L (the light), the ratio is zero. If L suddenly increases, the ratio becomes positive; if the increase is maintained, A builds up to L and the ratio lapses back to zero. If L suddenly decreases, the ratio becomes negative and then, as A reduces to L, returns to zero. If L increases or decreases by a fixed fraction of its value, the response is a fixed change in the ratio. Finally, a sudden increase of L to an immense multiple of A can only drive the ratio to a value approaching 1; a sudden decrease of L to a minute fraction of A can only drive the ratio to a value approaching -1. Indeed, the ratio can never go beyond ± 1 (the so-called compression limits).

You must imagine now a sheet of cones, each of which incorporates this strategy. If they were all independent of one another, any image whatever, stabilized on that sheet, would give zero signal everywhere. Conceive of the cones, however, as interconnected laterally, so as to communicate the A's to one another with a strength inversely related to distance. A stabilized image still gives zero signal everywhere. Yet a change in L at any cone is now read not only with respect to the cone's own adaptation level, A, but also with respect to all the A's of the cones around it. That is, the individual cones provide a temporal average of the dark light and their interconnections provide a spatial average. Three interconnected sheets of such cones, one for each of the three cone pigments and interdigitated with one another, provide a trichromatic reference for a change in L in any part of the image. The output signals tell nothing of the normalizations that underlie them; they have automatically adjusted themselves to compensate for changing circumstances of illumination. The system is well on its way to achieving color constancy.

At this point diversity, as a feature of the real world, enters in an important role. Diversity provides that the history of all local retinal areas, for an eye that moves about, is on the whole much the same. It also provides that the average of the various lights falling on any local retinal area has a good chance of approaching the average for the wider visual field around it. Further, it provides that the spatial averages resemble the temporal averages. Hence the diversity of the world ensures that local comparisons across boundaries have a good chance of yielding reliable color constancies for an entire scene.

Diversity applies not only to the distribution of reflected lights but also to the distribution of reflectance ratios across boundaries and around vertexes. These ratios are largely independent of the relative sizes of the areas that are bounded, so that these ratios are the basic information in vision, an imbalance in size between neighboring areas becomes unimportant over a fairly wide range of imbalance. Indeed, in the fourth display a small area of marked spectral dissimilarity from the ordered background is enough to ensure the color constancy of the adjacent gray hexagon.

To what extent does this color theory apply to the human visual system? It is known that the visual system employs a succession of processing stations. The cones pass information to neural circuitry in the retina, which recruits further stations by means of its output channel, the optic nerve. The nerve engages the brain structure called the lateral geniculate body, which in turn engages the part of the cerebral cortex called the primary visual cortex. The cones, then, are the very first elements in a complex sensory system. It may seem surprising that we assign them (and their interconnections) so much responsibility in the color process.

Physiological evidence has established, however, that the detection of boundaries and vertexes begins in the retina. And since each boundary signifies a change in quality (a difference in color or brightness, for instance), the detection of a boundary implies the prior existence of that quality, so that a difference can be detected. (Distinguishing a boundary between red and green implies the prior distinction of redness and greenness.) It would be extremely uneconomical, and also unreliable, for the retina to defer the color process to later stages of the visual system by exporting information about qualities such as color by channels that are separate from the channels that signal boundaries. Moreover, it would take up an inordinate amount of channel space.

Simple economy leads, therefore, to the position that the processing of color determinants by the cones and their intimately associated retinal apparatus offers a reliable system—one that is preferable, we think, to any deferred processing by more central tissue, such as the visual cortex. It remains to be seen whether this is the strategy nature has chosen.

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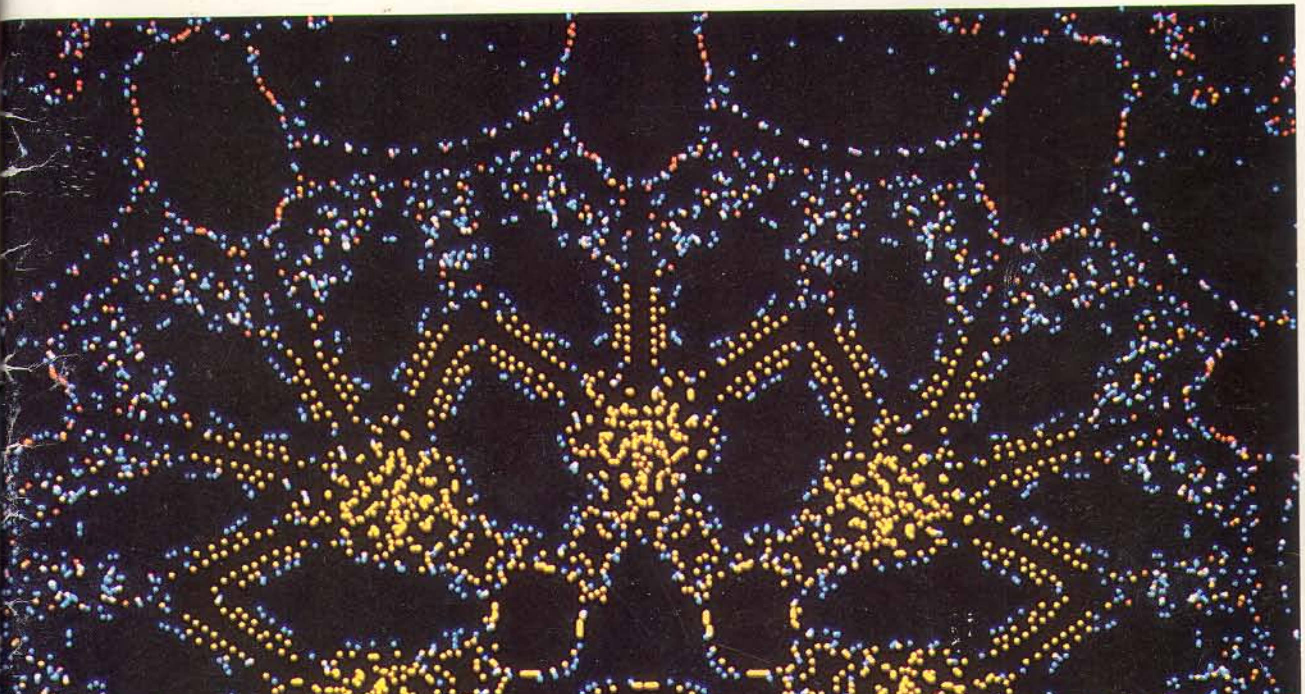

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