Hidden Visual Processes

Vision is usually regarded as being a single sense. Experiments show, however, that the visual system includes subsystems whose operation is normally hidden from the awareness of the perceiver

by Jeremy M. Wolfe

From the standpoint of a person contemplating his abilities to perceive the world, vision seems to be a single sense. The images impinging on the two retinas give rise to a single awareness of the objects in the world: their sizes, shapes, colors, textures and positions. This view, however, is mistaken. The visual system (the brain mechanism that processes data from the eyes) is actually a set of specialized subsystems each of which acts more or less independently on some subset of visual data. Furthermore, some of the visual subsystems have an output that cannot be seen. They contribute to brain function and even to our awareness of the world, but no amount of introspection can make us aware of the subsystems themselves. They perform hidden visual processes.

How is a hidden process revealed? One way is to examine the abilities of people who have suffered brain injury. Consider the pupil of the eye, which constricts in response to an increase in the intensity of light falling on the retina. If someone suffers an injury that destroys the visual cortex (the part of the cerebral cortex first in line to get data from the eyes), he is rendered perceptually blind. That is, his awareness of a loss of vision is the same as that of someone who has lost the use of the eyes themselves. Nevertheless, the pupils continue to constrict in response to light. Even more strikingly, Ernest C. Poppel, Richard Held and Douglas Frost of the Massachusetts Institute of Technology have found that when people who are perceptually blind because of an injury to the cerebral cortex are asked to direct their eyes toward a spot of light, they do surprisingly well. The subjects report that they cannot see the spot, and so they think they are guessing, but they look in roughly the right direction more often than chance would allow.

Brain-injured people thus show evidence of multiple visual processes: some that are damaged, and hidden ones that remain functional. What such studies cannot confirm is that similar hidden processes operate in people whose visual system is intact. For that, special experimental strategies are required. Here I shall describe three sets of experiments each of which reveals a visual process that in normal people is hidden from introspection. In this regard all of us are like the brain-injured patient who can look at a spot of light although he cannot perceive it. We too are unaware of the abilities of certain parts of the visual system even though our behavior is often based on their output.

One of the functions of the visual system is to control the muscles that focus the eye on objects at various distances by changing the shape of the lens. The closer the object is, the more nearly spherical the lens must be. The process is called visual accommodation. One's impression is that one can accommodate for anything one can see. It is natural to assume, therefore, that accommodation and visual perception have access to the same set of stimuli.

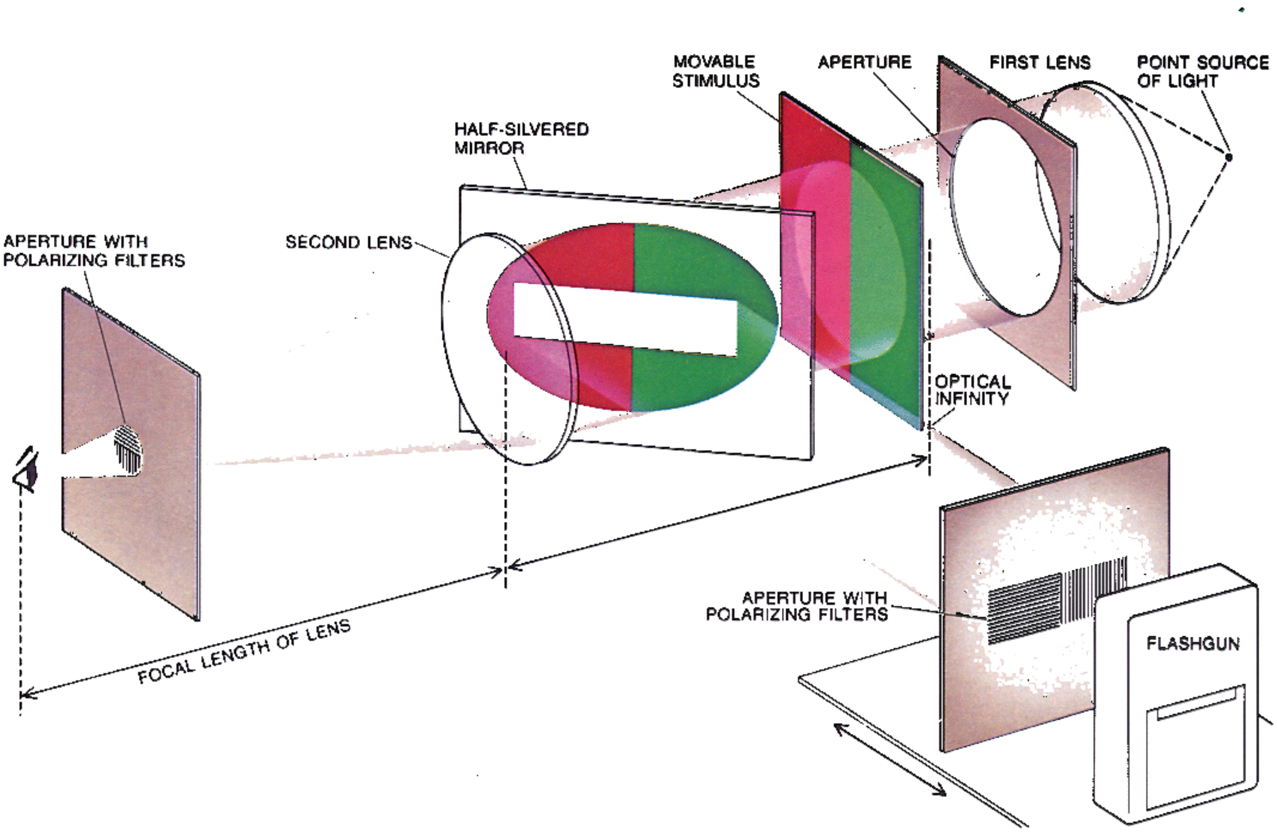
Do they? By means of a number of experimental methods the accommodative status of the eye can be measured while the subject looks at a stimulus placed a certain distance from him. In one such method the subject views the stimulus through polarizing filters, and a flash of light from behind a slit briefly superposes on the stimulus a bright horizontal bar. The filters have no effect on the stimulus, but they ensure that light from the left half of the bar will enter only the top of the lens of the subject's eye and light from the right half will enter only the bottom.

Suppose a subject who is looking at the stimulus is accommodating for a distance greater or less than the distance to the slit. If the bar is flashed at that instant, the two halves of it will be misaligned on the retina and the subject will see them as being offset. Hence the experimenter need only have the subject look at the stimulus while the bar repeatedly appears and ask the subject whether or not its halves are aligned. The slit is moved to various distances until the subject reports that they are aligned. The distance from the slit to the eye is then the distance for which the subject is accommodating.

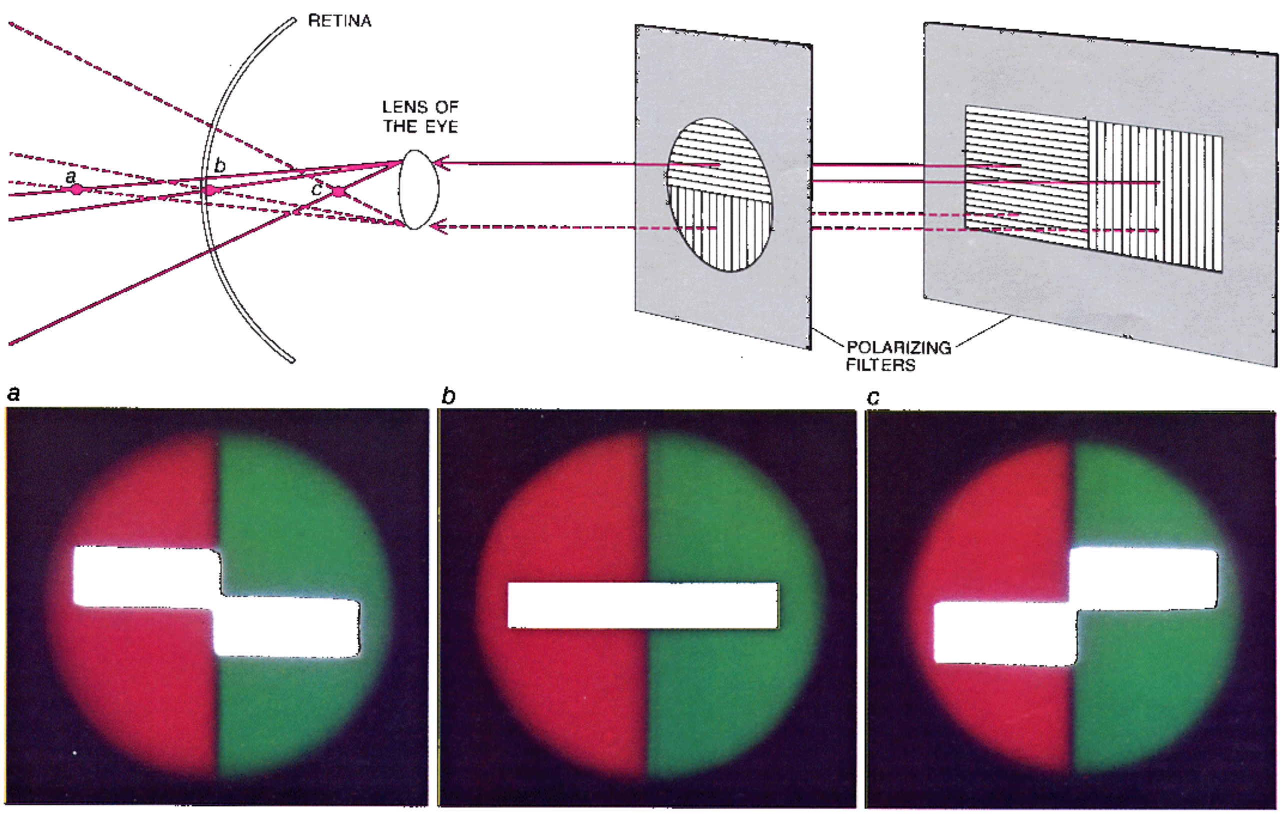
The lens of the eye hardens with age, and so it is best to study accommodation in subjects no older than their 30's. In the laboratory such subjects can be shown stimuli that change only in distance, not in brightness and size. This eliminates all perceptual clues to the distance of the stimulus except the fact that a certain accommodative state brings the stimulus to a focus. Under these circumstances the typical subject's accommodation is about 90 percent of perfect. (If it were perfect, a stimulus at a distance of 25 centimeters would cause the eye to accommodate for a distance of 25 centimeters and so on.)

How does the eye respond when the stimulus has no features for the eye to focus on? One such stimulus would be a blank screen surrounding the subject; the experience is like being inside a giant ping-pong ball. Another stimulus would be a smaller blank screen viewed through a lens that makes the screen appear too close (in optical, or apparent, distance) for the eye to focus

ISOLUMINANT STIMULUS is an image whose edges are defined only by a change in color, not by a change in brightness. The stimulus here is imperfect: the blue parts and the green parts of the image are only as nearly equal in brightness as they can be on the printed page. Moreover, the change in brightness beyond the edge of the page is apparent, and so is the fact that the reader is holding the magazine at reading distance. When such cues are removed under laboratory conditions, subjects faced with an isoluminant stimulus prove unable to bring its edges into focus. This deficiency contributes to making a familiar face hard to recognize. The experiment indicates that the brain process underlying visual accommodation (the focusing of the eyes) cannot "see" color; it is a hidden process distinct from the processes that lead to perception. The image shows Groucho Marx as he appeared in the motion picture *Horse Feathers*.



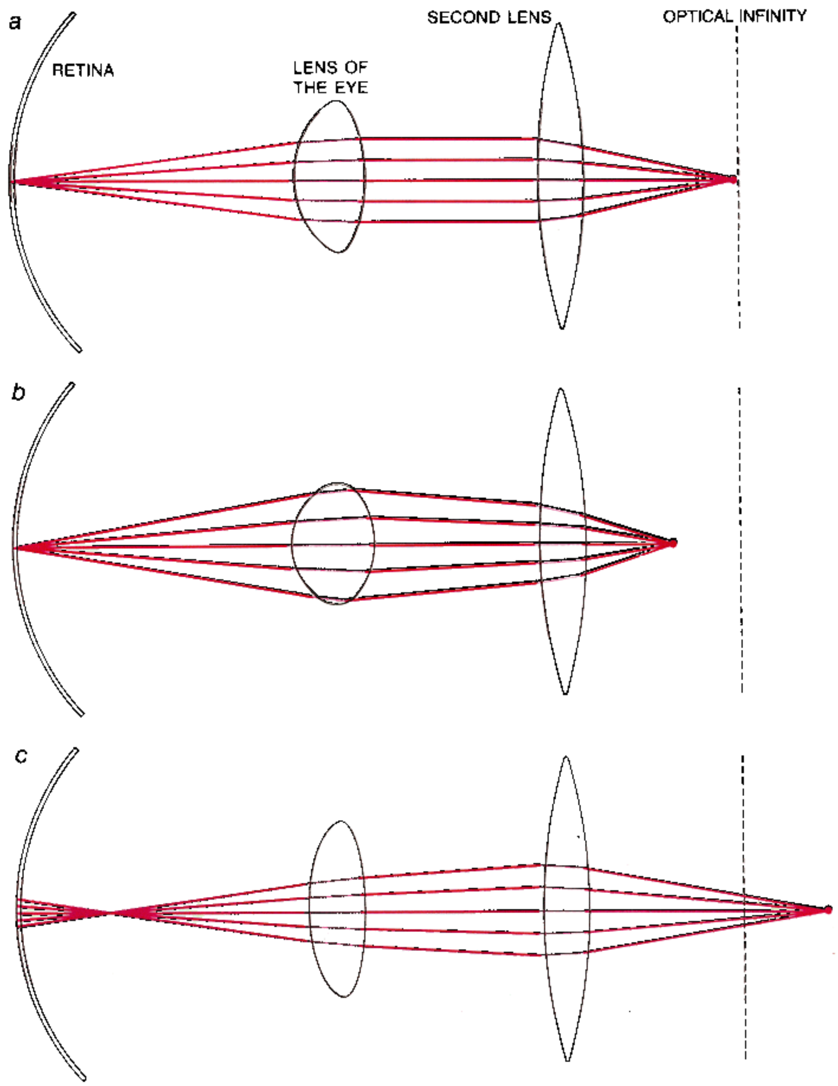
EXPERIMENTAL APPARATUS tests the ability of the eye to accommodate for an edge in an isoluminant stimulus. The lens toward the upper right in the illustration collimates a beam of light. The beam passes through an aperture, then through the stimulus, which has a vertical edge defined only by the colors red and green. A second lens directs light into the subject's eye. A further arrangement consisting of a flashgun, a movable slit and a half-silvered mirror briefly superposes on the isoluminant stimulus a horizontal bar of light.



ACCOMMODATION IS MEASURED by having people describe the flashing horizontal bar. A series of polarizing filters ensures that light from the left side of the bar enters only the top of the lens of the subject's eye; light from the right side enters only the bottom. The two sides of the bar will line up on the retina (*b*) only if the subject happens to be accommodating for the distance to the movable slit.

on its edges. Another would be a featureless sky; still another would be complete darkness. Herschel W. Leibowitz and D. Alfred Owens of Pennsylvania State University have found that in any of these circumstances the lens of the eye assumes a rather stable resting curvature for a particular focal distance called the dark focus. Each individual has a characteristic dark focus that is usually about one meter, or about an arm's length from the eye.

The same thing happens when the stimulus is a grating of black and white lines so fine that they give the impression of a gray field. Here again the experimenter's lens can place the stimulus at a variety of optical distances. When the stimulus is at an optical distance of 25 centimeters, the lens of the subject's eye assumes its resting state. When the stimulus is moved to an optical distance of one meter, the subject's accommodative state shows no change. The conclusion is that accommodation can shape the lens of the eye to keep an object in focus only if the system responsible for accommodation is presented with something it can "see."



OPTICAL DISTANCE of a stimulus is the apparent distance given the stimulus by the second lens in the experimental apparatus. If the stimulus is positioned at the focal length of the lens (*a*), it will be at optical infinity, that is, the light rays from each part of the stimulus will approach the eye in parallel, as if they came from a source infinitely far away. The lens of the eye will assume a curvature that brings the rays to a point on the retina. If the stimulus is closer than optical infinity (*b*), the rays will diverge as they approach the eye. The lens of the eye will then assume a more nearly spherical shape to bring the rays to a focus. If the stimulus is farther away than optical infinity (*c*), the rays will converge as they approach the eye. The lens of the eye will be unable to reduce its curvature to the required extent; thus the rays will come to a point in front of the retina. A stimulus beyond optical infinity cannot be brought into focus.

Armed with the knowledge that the accommodation system is blind to certain aspects of the visual world, Owens and I asked whether the system can "see" color. We measured accommodation while our subjects looked at a simple stimulus: a circular field divided vertically in half so that it included a single vertical edge. An optical system known as Maxwellian-view optics ensured that the perimeter of the circle was beyond optical infinity. That is, the rays of light from each point on the perimeter of the circle were made to enter the eye in such a way that they could never be brought into focus whatever shape the lens of the eye assumed. As a result the vertical edge between the two halves of the field was really the only edge in the stimulus for which the eye could accommodate. The optical system was also designed to ensure that the image of the stimulus would keep the same size on the retina when we changed its optical distance.

The edge itself could be created by a difference in either color or brightness between the two half fields. In the real world most contours arise from a difference in both. We chose to make one half field red, the other green. Then we varied the brightness of one half field or the other. In this way we created stimuli ranging from an edge between red and black to an edge between black and green. At each extreme the contrast in brightness across the edge between the color and the black was 100 percent. In the precisely intermediate case, however, the red and the green were equally bright. They formed an isoluminant stimulus whose single edge was defined only by color. The contrast in brightness was zero.

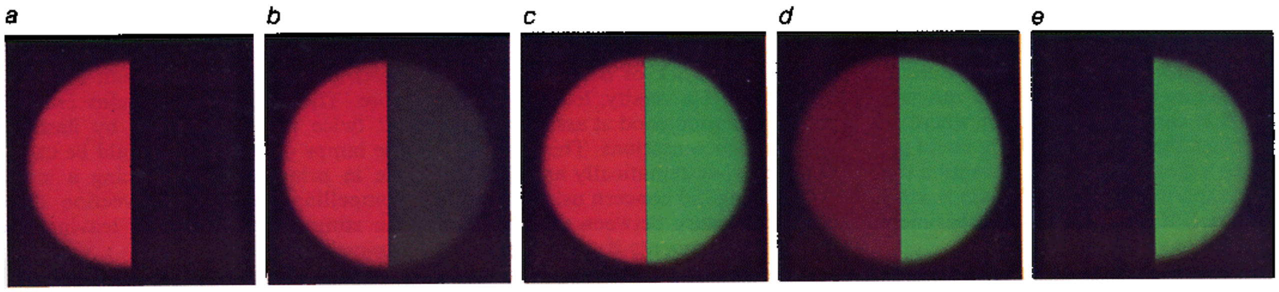
When we tested people's ability to accommodate for each of these stimuli, we found the ability declined as the contrast in brightness declined. Thus our subjects could readily tell that the isoluminant stimulus was an edge between red and green, but it was impossible for them to bring the edge into focus. In one experiment we had subjects look at a black *E* on a white background. The subjects accommodated quite well for optical distances from infinity down to 22 centimeters. Then we had them look at edges between red and black or between black and green. Their accommodation was about 80 percent as good as the best they had done for the *E*. Finally we showed them the red-green edge that has no contrast in brightness. Their accommodation was only 19 percent as good. When we repeated the experiment with pairs of colors such as red and orange or blue and green, the subjects' performance was equally poor or worse.

Like any other optical system, the eye has a chromatic aberration, which brings different colors to a focus at slightly different focal lengths. The aberration therefore tends to shift the retinal image of one color half field with respect to the image of the other. This can give rise to a bright or dark contour depending on whether the images separate or overlap. As a result it is surprisingly difficult to create a stimulus that has absolutely no clues to the presence of an edge except the difference in color itself. We suspect our subjects' performance would have been even worse than it was if chromatic aberration could have been eliminated. Still, the conclusion seems clear: accommodation is colorblind, or at least it "sees" color very badly. It is a visual subsystem remarkably independent of visual perception. Here, then, is a finding that no amount of introspection could have suggested about vision.

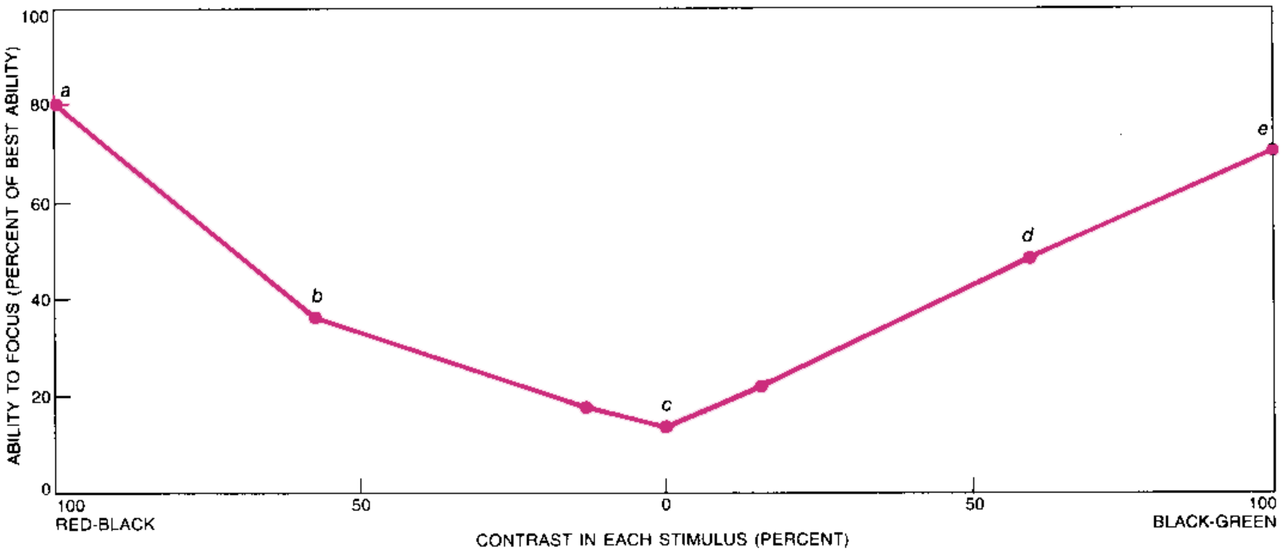
A second strategy for exploring the division of the visual system into subsystems is to consider the ways a particular visual function is performed by different parts of the system. One such function is binocular vision. A normal person has two eyes, and the brain makes every effort to integrate the data from them. It is becoming clear, however, that the brain does more than simply combine the inputs from the eyes in one grand binocular process that leads to visual perception. Instead several special-purpose mechanisms combine the inputs in their own way to meet their own particular needs. Just as no amount of introspection will reveal that accommodation is colorblind, so no amount of introspection will reveal these multiple binocular processes. Nevertheless, the processes do exist and can be revealed by experimentation.

Consider a visual illusion that everyone has experienced in one form or another. You are sitting in a train, waiting for it to pull out of the station. Looking out the window, you see another train motionless on the adjacent track. The other train's image starts to slide backward, and you distinctly feel that your train is moving forward. Then you see it is the other train that has moved; your train is still in the station. The motion of the other train somehow deluded you into believing you were moving. You have experienced an illusion of motion created solely by visual stimulation. The illusion is known as vection.

Several investigators have sought to examine the brain mechanism responsible for vection. Held and I became interested in a rather different question. We wanted to know what the vection process can "see." In particular we wanted to know if the process can make use of people's ability to look at the world through two eyes. One might think the answer could be found quite easily by comparing the vection experienced when both eyes are open with the vection experienced when only one eye is open. Normally, however, the sensation of vection is already at its maximum when only one eye is open; the illusion of self-motion cannot be more pronounced. One



STIMULI FOR THE EXPERIMENT on the ability to accommodate vary from an edge between red and black (*a*) to an edge between black and green (*e*). The precisely intermediate stimulus (*c*) is isoluminant. The circular perimeter of each stimulus is defined by an aperture placed well beyond optical infinity in the experimental apparatus; hence the subject's eye cannot bring the perimeter into focus.



ABILITY TO FOCUS on the stimuli turns out to depend on their contrast in brightness. Here the average performance of four subjects is charted as a percentage of the ability they had when they looked at black letters on an eye-examination chart. The subjects' performance grows poorer with decreasing contrast. It is worst (19 percent of the best performance) when the stimulus is isoluminant.

needs, therefore, to create a stimulus whose binocular effect could conceivably be greater than its monocular effect. Such a stimulus must have a purely binocular component: there must be something about the stimulus that is invisible to each eye by itself.

A component that meets this requirement is called a cyclopean stimulus, after the Cyclops, the Homeric one-eyed creature encountered by Odysseus. The name is apt because a cyclopean stimulus is evident only if the brain combines the input from the eyes. In effect the brain must act as a single, cyclopean eye. One example of a cyclopean stimulus is the small difference in position between the image of an object in the world on each of the retinas. The difference can easily be seen. Stretch out one of your arms and look at the tip of a finger first with one eye closed and then with the other eye closed. You will notice that the two views are slightly different. The brain exploits such differences in the processes that lead to the perception of three-dimensional depth. Clearly the brain must draw on data from both eyes for the stimulus to exist.

Our cyclopean stimulus for vection capitalized on the well-known fact that objects seen in a motion picture seem to move smoothly even though they are presented in a succession of still photographs. Our subjects sat inside a cylinder three feet in diameter and five feet high. The inside surface of the cylinder was white and was covered with a random pattern of black dots an inch in diameter. The cylinder rotated about the subject at the rate of 30 degrees of angle per second. When the inner surface of the cylinder was illuminated by ordinary lighting, the subject reported a sensation of rotation in the opposite direction. For our experiments we illuminated the surface with the periodic flashes of a stroboscopic lamp. Each flash produced the equivalent of a frame from a movie of black dots. The subject reported the same sensation of vection.

To create a cyclopean stimulus two strobe lamps were needed. One was covered with a red filter, the other with a green filter. The subjects wore goggles that placed a red filter in front of one eye and a green filter in front of the other. No red light could pass through the green filter; no green light could pass through the red. Hence the light from one strobe lamp was seen by one eye and the light from the other strobe lamp was seen by the other eye.

Suppose each strobe lamp is flashing at 10 hertz, or 10 times per second. If the two lamps are flashing in phase (that is, in synchrony), the subject should notice no important difference in looking with two eyes rather than one. In either case he will see in effect a 10-frame-per-second movie of moving dots. Suppose, however, the strobe lamps are exactly out of phase, so that they flash in alternation. Now there is a difference. A subject who has only one eye open will see again a 10-frame-per-second movie. With both eyes open he will see an additional movie. It will appear at a rate of 20 frames per second, and it will consist of frames presented in alternation first to one eye, then to the other, then to the first eye again.

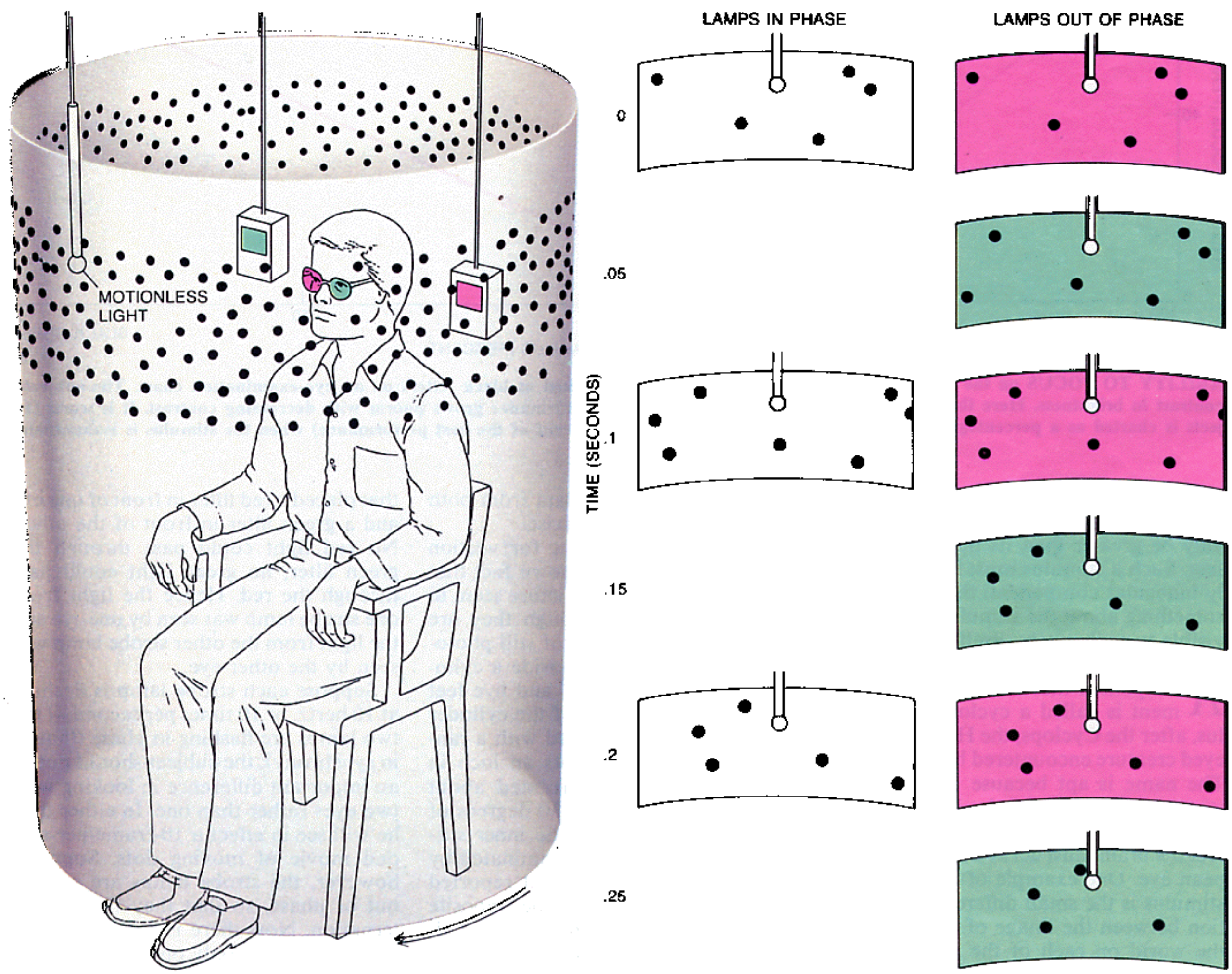
The 20-hertz interocular movie is thus

a cyclopean stimulus: it cannot be seen by either eye alone. It does give rise to the appearance of motion. The question is whether the vection system can "see" it. If it can, the experiment where the strobe lamps are out of phase could produce a greater sensation of vection than the experiment where the lamps are in phase. If it cannot, the two experiments should have the same result.

With our apparatus in place we prepared subjects for the experiments. In particular we taught them a method known in experimental psychology as magnitude estimation. We asked them to give a rating of 10 to a compelling sensation of self-motion and one of zero to no sensation of motion. Ratings between 0 and 10 were to be given to sensations between these two extremes. Unlikely as it may seem, some 25 years of research in experimental psychology, notably the work of S. Smith Stevens of Harvard University, has shown that people are quite good at assigning numbers to their sensations. They can do it repeatedly, systematically and reliably.

One thing did concern us: there could be no difference between the results of the two experiments if the sensation of vection yielded the maximum rating of 10 when the lamps were in phase. If the frames of a movie are shown at a progressively lower rate, the illusion of motion becomes progressively less compelling. In the same way the flicker rate turns out to be important to the sensation of self-motion. We found that any rate higher than about 2.5 hertz produced some degree of vection, but only rates higher than about 15 hertz consistently earned ratings of 10 from our subjects. Therefore flicker rates between 2.5 hertz and 15 hertz would suit our purpose. The cyclopean stimulus created (at twice the flicker rate) by flashing the lamps out of phase would be capable in principle of producing a more compelling sensation of vection than the stimulus produced by leaving the lamps in phase.

Our findings were straightforward. For any flicker rate between 2.5 hertz and 15 hertz the two strobes out of phase always elicited the greater magnitude estimates. Evidently the vection system can "see" the purely binocular stimulus. Does this result establish that the brain has multiple binocular processes? Not in itself. As I have noted, the slight difference in position between the images of an object on each retina is



EXPERIMENT WITH VECTION (the sensation of bodily motion arising from the motion of the visual world) requires that subjects be seated inside a rotating cylinder whose inner surface is white and is covered with a random pattern of black dots. Two stroboscopic lamps illuminate the surface in flashes of red and green light; a pair of goggles allows the light of each color to enter one eye only. If the lamps flash in phase (that is, synchronously) at a rate of 10 flashes per second, a subject with one eye open sees what a subject with both eyes open sees: in effect a 10-frame-per-second motion picture of moving dots. If the lamps flash out of phase, a subject with one eye open sees the identical movie, but a subject with both eyes open sees an additional movie. It appears at a rate of 20 frames per second, and it is interocular: its successive frames are seen by the two eyes in alternation. A small stationary light serves as a reference point.

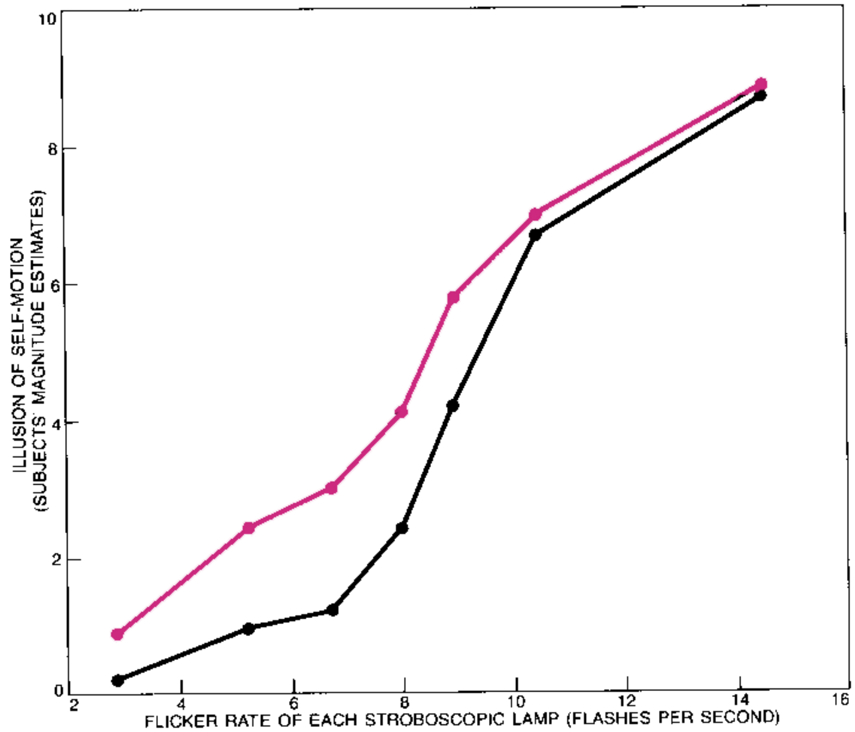
a cyclopean clue to three-dimensional depth. It is conceivable that the binocular mechanism serving this aspect of visual perception also serves the binocular contribution to vection.

Some people, however, cannot perceive depth on the basis of cyclopean stimuli. For example, they cannot get the illusion of depth when they look at an image through a stereoscope or when they go to a "3-D" movie. They are stereoblind. Some of them are born that way, just as some people are born colorblind. Others lose the ability because of defects that develop in infancy in the ability to align the eyes. Stereoblindness is somewhat rarer than colorblindness; it seems to affect only a few percent of the U.S. population. A person who is stereoblind can still perceive depth on the basis of visual cues such as the apparent size of familiar objects or the fact that some objects in the visual field block others that are farther away. These monocular cues to three-dimensional depth are quite good; many people who are stereoblind do not know they are until a test reveals it.

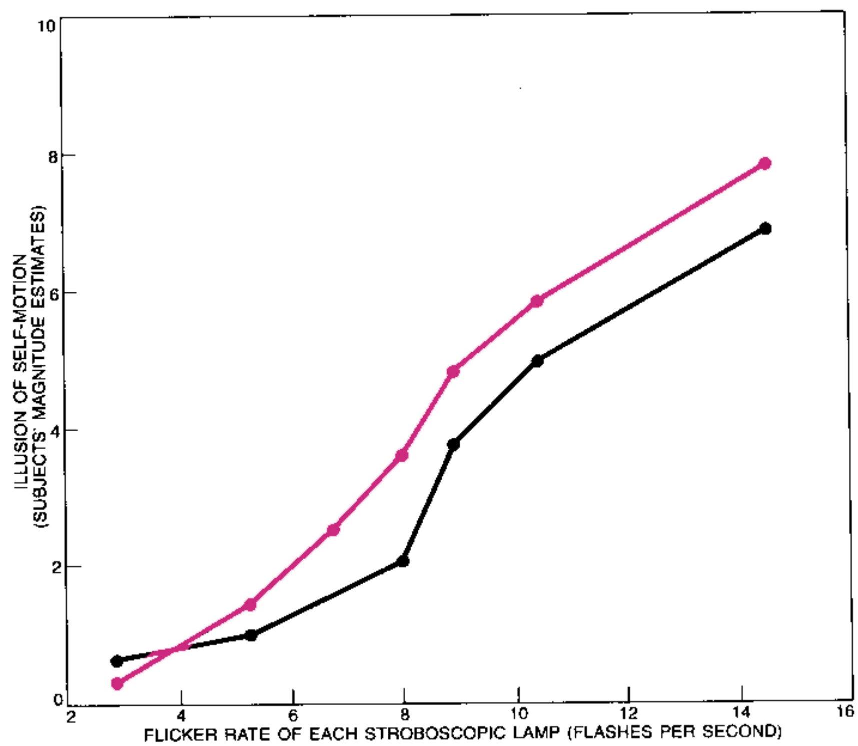
Held and I asked four people who had been established as stereoblind to be subjects in our vection experiments. Their magnitude estimations were much like those of our normal subjects. They too got an increased sensation of self-motion from the purely binocular stimulus. Here, then, are people with a defective binocular mechanism who nonetheless prove to be perfectly normal in experiments requiring that their brain employ a binocular mechanism. Thus the defective mechanism cannot be the only binocular mechanism in the brain. There must be at least two binocular mechanisms, one mediating stereoscopic depth perception, the other involved in the production of vection. The experiments again show that visual data feed more than one processing system.

The two hidden visual processes I have now described (the colorblind visual process that controls accommodation and the binocular visual process that contributes to vection) appear to play no direct role in visual perception. Other hidden visual processes do take part in perception.

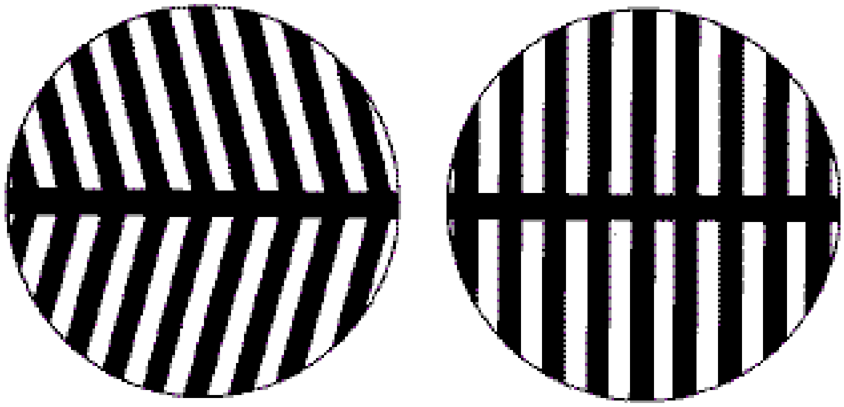
For an example I shall return to the binocular visual processes. Our experiments with vection revealed two binocular processes. The experiments I shall now describe show more. Indeed, there emerges a remarkable assortment of processes. Between our two eyes and our single perception of the visual world lie processes that can "see" out of one eye, processes that can "see" out of either eye and, most surprising, a purely binocular process: a process that can "see" only out of both eyes. In fact, it can "see" only when both eyes are looking at the same stimulus. If your visual



SENSATION OF VECTION is greater if the lamps are out of phase (*color*) than it is if the lamps are in phase (*black*), showing that the brain process responsible for vection can "see" a movie created by stimulating the eyes in alternation. It is thus a binocular process. The data in the chart were collected by asking six subjects to assign ratings in which 10 signified the most compelling illusion of bodily motion whereas zero signified the absence of such an illusion.



RATINGS BY STEREOBLIND SUBJECTS show that they too have a greater sensation of vection if the lamps are out of phase. People who are stereoblind lack the binocular visual process that compares the images from the eyes to aid in the perception of three-dimensional depth. Hence the process responsible for vection must be a different binocular process. The data in the chart were collected from four stereoblind subjects, who rated their sensations.



TILT AFTEREFFECT is an illusion that serves the study of hidden visual processes on the pathways leading to visual perception. To experience the illusion let your eyes scan back and forth along the horizontal black bar crossing the chevron at the left side of the illustration. You should then find that the two halves of the pattern at the right are briefly not colinear. The tilt aftereffect is measured by making the pattern at the right adjustable and asking subjects to adjust it so that it seems to be colinear immediately after they have stared at the chevron.

system had only the purely binocular process, you would be unable to see if one eye was closed. You would be unable to see when you tried, for example, to peek out from behind a tree and one eye surveyed only tree bark while the other surveyed a house.

The ability to perceive a purely binocular stimulus such as the cyclopean stimulus that served our study of vection does not ensure that the brain has a purely binocular visual process. The cyclopean stimulus could have been "seen" by a visual process that accepts input from both eyes and also from either eye alone. How, then, is it known that a purely binocular process is there? Again one resorts to an indirect method, in this case based on a temporary distortion of vision called the tilt aftereffect.

Look at the pattern of stripes at the right in the illustration above. The top half of the pattern should appear to be aligned with the bottom half. Now look at the chevron pattern at the left in the illustration. Let your eyes scan back and forth for one or two minutes along the horizontal black bar that crosses the center of the chevron, then quickly shift your gaze to the pattern at the right. You should find that the two halves no longer seem aligned. They should appear to be bent in the direction opposite to the direction of the bend in the chevron.

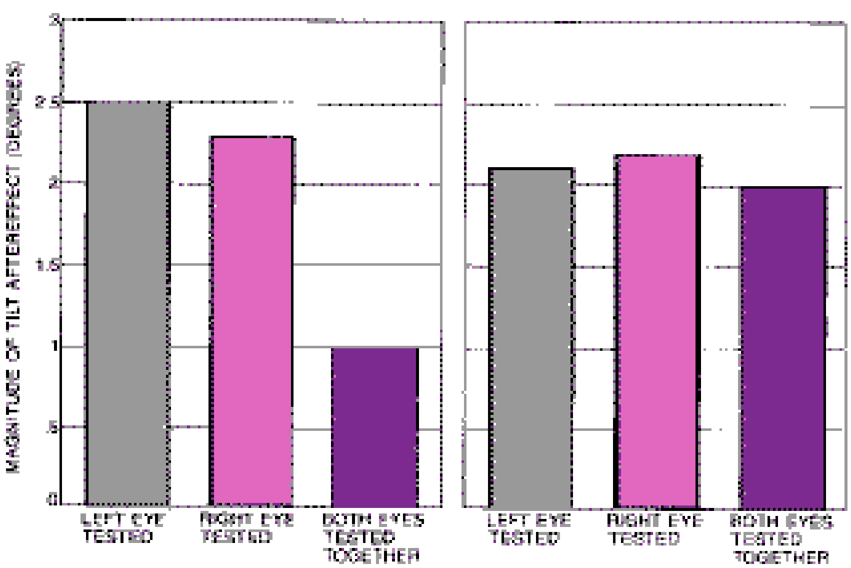
This is the tilt aftereffect. It can be measured by making the two halves of the pattern at the right adjustable and asking people to make the two halves look aligned. Before people view the chevron they make settings quite close to colinearity. After viewing the chevron their settings are systematically displaced by about two degrees.

Suppose a subject looks at the chevron with only his right eye open and then manipulates the adjustable pattern with only his left eye open. The left eye never sees the chevron, yet an aftereffect is detected. In short, there is interocular transfer. It is evidence for a binocular process but not a purely binocular one. After all, the process was activated when the right eye was exposed to the chevron and it was activated when the left eye was tested with the adjustable pattern. Apparently it can respond to either the left eye or the right.

As it happens, the aftereffect is smaller when it is tested with the eye that was not exposed to the chevron than it is when it is tested with the eye that was exposed. Only 70 to 80 percent of the aftereffect transfers. Randolph Blake and his colleagues at Northwestern University conclude from this finding that at least two processes are involved when the tilt aftereffect is tested with one eye. One of them is the binocular process; the other one is monocular. Thus the exposure of the right eye to the chevron activates both the binocular process and the right eye's monocular process. The testing of the right eye activates both of them again. The result is a strong tilt aftereffect. Suppose the left eye is tested. The binocular process, which was exposed to the stimulus, becomes active again. The left eye's monocular process also becomes active, but it never "saw" the chevron. Its output dilutes the magnitude of the aftereffect.

By means, then, of the tilt aftereffect Blake demonstrated the existence of both monocular and binocular processes. Held and I exploited the aftereffect to show that a purely binocular process exists as well. We had subjects look at the chevron with each eye in alternation: one minute with the left eye, one minute with the right eye, one minute with the left eye again and one minute with the right eye again. When we measured the aftereffect, we had them keep either the left eye open, the right eye open or both eyes open.

We reasoned that the alternating monocular viewing of the stimulus would expose every visual process that gets input from the left eye, every proc-



PURELY BINOCULAR PROCESS is revealed by comparing the results of two experiments that employ the tilt aftereffect. In one of the experiments (*left*) subjects stared at the chevron with each eye open in alternation; thus the stimulus was available to every visual process that gets input from one eye and every process that gets input from either eye. On the other hand, the stimulus was unavailable to a purely binocular process: one that gets input only from both eyes. The subjects then manipulated the adjustable pattern with one eye or with both eyes open. The binocular aftereffect proved to be less than the monocular aftereffect. The second experiment (*right*) differed only in that the subjects stared at the chevron with both eyes open. The binocular aftereffect now proved to equal the monocular aftereffect. Evidently the binocular viewing of the stimulus in the second experiment exposed the purely binocular process.

ess that gets input from the right eye and every process that gets input from either eye. If these were the only visual processes, they would constitute the entire visual system. Hence it would make no difference whether the subject had one eye open or both eyes open when he manipulated the adjustable pattern; the tilt aftereffect would be the same. If, however, there were a visual process that is active only when the left eye and the right eye are stimulated simultaneously, the results would be different. The alternating monocular viewing of the stimulus would leave this process unexposed, but then if both eyes were opened for the test of the aftereffect, the process would be activated, and it would dilute the aftereffect.

That is in fact what we found. The magnitude of the aftereffect was much less with both eyes open than it was with one eye closed. In a further experiment we had subjects look at the chevron with both eyes open. We expected this would expose every visual process, and we were right: the aftereffect was now much the same whether the subjects had both eyes open or one eye open when they manipulated the adjustable pattern.

In both experiments the left eye and the right eye were both exposed to the chevron. The only difference is that in the first experiment our subjects never saw the chevron with both eyes open at the same time. In the second experiment they did. A process was left unexposed by the first experiment and then was exposed in the second. That process must "see" only with both eyes. It is a purely binocular process.

What could a purely binocular process do in assistance of vision? In order to perceive three-dimensional depth the visual system seeks matches and slight mismatches between features in the images in each eye. The purely binocular process could serve in such a search. Visual perception cannot, however, be based on the output of a purely binocular process alone. If it were, all the unmatched parts of the two retinal images would vanish. In fact what we cannot see by means of a purely binocular process we can see by means of a monocular process or a process that responds to either eye.

From ancient times people have spoken of five senses. It is becoming ever clearer, however, that five is much too small a number. Senses such as touch seem to be divided into a variety of submodalities; the visual system is also divisible. Perhaps vision is best regarded not as a single sense but as a set of systems, each one a sense in its own right. It is likely that the full range of human visual senses remains to be discovered. The senses are like an old and crowded attic in that one finds the unexpected in each new corner one explores.