Blind Spots

Investigating how the visual system compensates for gaps in perception is helping researchers to elucidate how the brain processes images

by Vilayanur S. Ramachandran

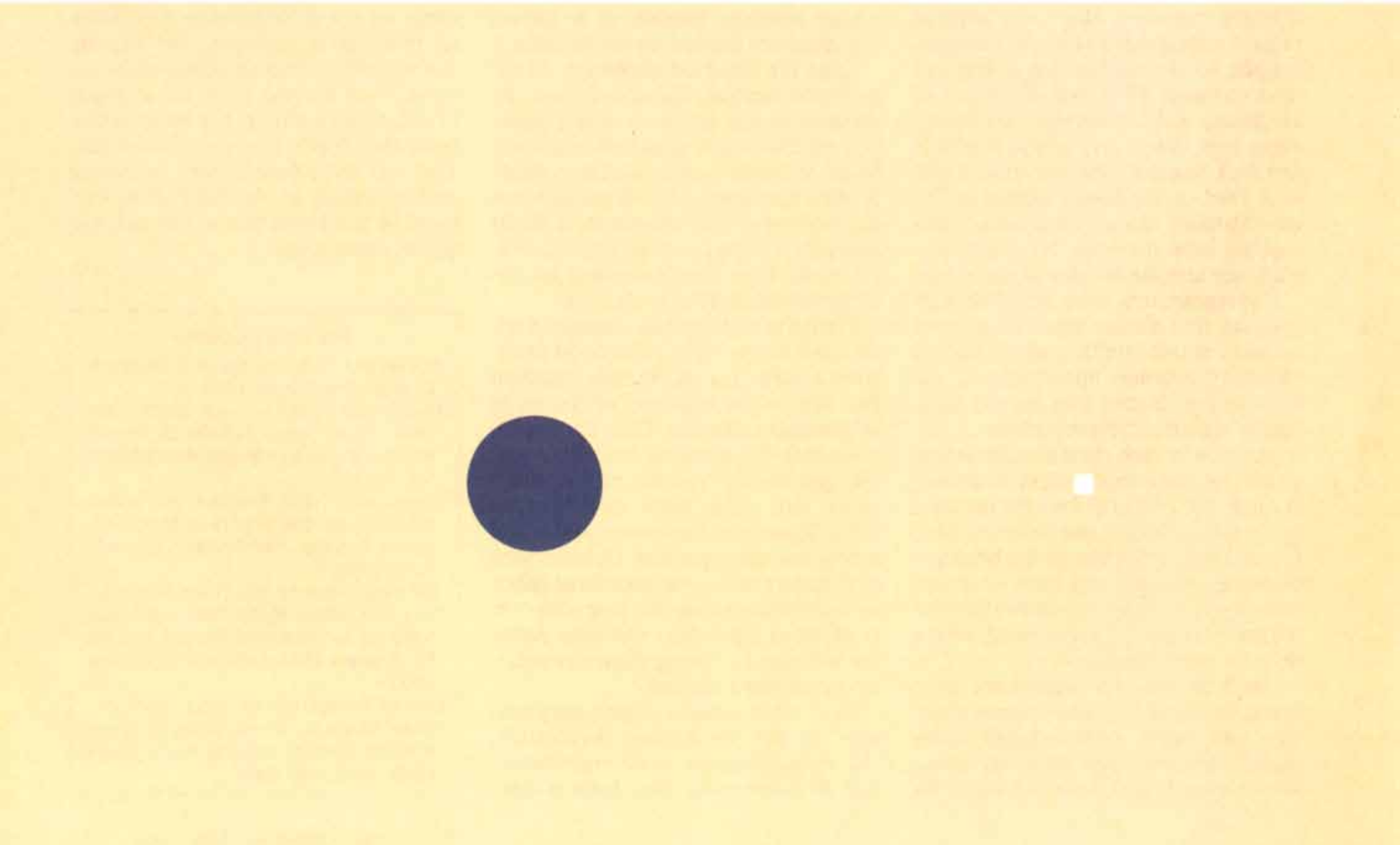
As he dissected a human eye, the 17th-century French scientist Edme Mariotte noticed the optic disk—the area of the retina where the optic nerve attaches to the eyeball. He realized that, unlike other parts of the retina, the optic disk is not sensitive to light. Applying his knowledge of optics and the anatomy of the eye, he deduced that every eye should be blind in a small portion of its visual field.

The reader can easily confirm Mariotte's conclusion by examining the illustration below of a disk on a colored background. Close your right eye and hold the page about a foot away from your face. Concentrate on the square as you slowly move the illustration toward your eye. At some critical distance, the disk should fall within your blind spot and disappear completely. In fact, you should perceive the disk as covered by the color of the surrounding background. This visual process is known as filling in.

VILAYANUR S. RAMACHANDRAN is professor in the neurosciences program and psychology department at the University of California, San Diego. He obtained an M.D. from the University of Madras and went on to earn a Ph.D. in neurophysiology from Trinity College at the University of Cambridge. This is his third article for *Scientific American*.

Recently psychologists have begun to appreciate that filling in is a manifestation of a more general perceptual mechanism called surface interpolation. When a person looks at a table, for instance, it seems likely the visual system extracts information about its edges and creates a mental representation that resembles a cartoon sketch of the table. The visual system might then apply surface interpolation to fill in the color and texture of the table. Such a process would allow the visual system to avoid the computational burden of creating a detailed representation of surface colors and textures.

To understand how the brain interpolates visual information, my colleagues and I at the University of California at San Diego have conducted many experiments that test percep-



tion in the blind spot. The illustrations in this article offer the reader a chance to try a few of these experiments. To enrich our analysis, we have also investigated two types of "artificial" blind spots. First, we developed a harmless technique for inducing temporary blind spots. Second, we examined several individuals who suffer from scotomas—regions of blindness caused by damage to a small portion of the brain. The work has enabled us to discover many characteristics of the filling-in process, and we have begun to understand how filling in relates to other visual processes, such as edge detection and motion perception.

Psychologists have known for some time that if a person glances at an object, a perceptual representation of the object forms in the visual areas of the brain. In contrast, the brain uses another strategy to keep track of objects outside the visual field, such as those behind the head. For such objects, the brain creates what might be loosely called a conceptual representation, something similar to a logical inference. The distinction is not merely semantic. Perceptual and conceptual representations are probably generated in separate regions of the brain and may be processed in very different ways.

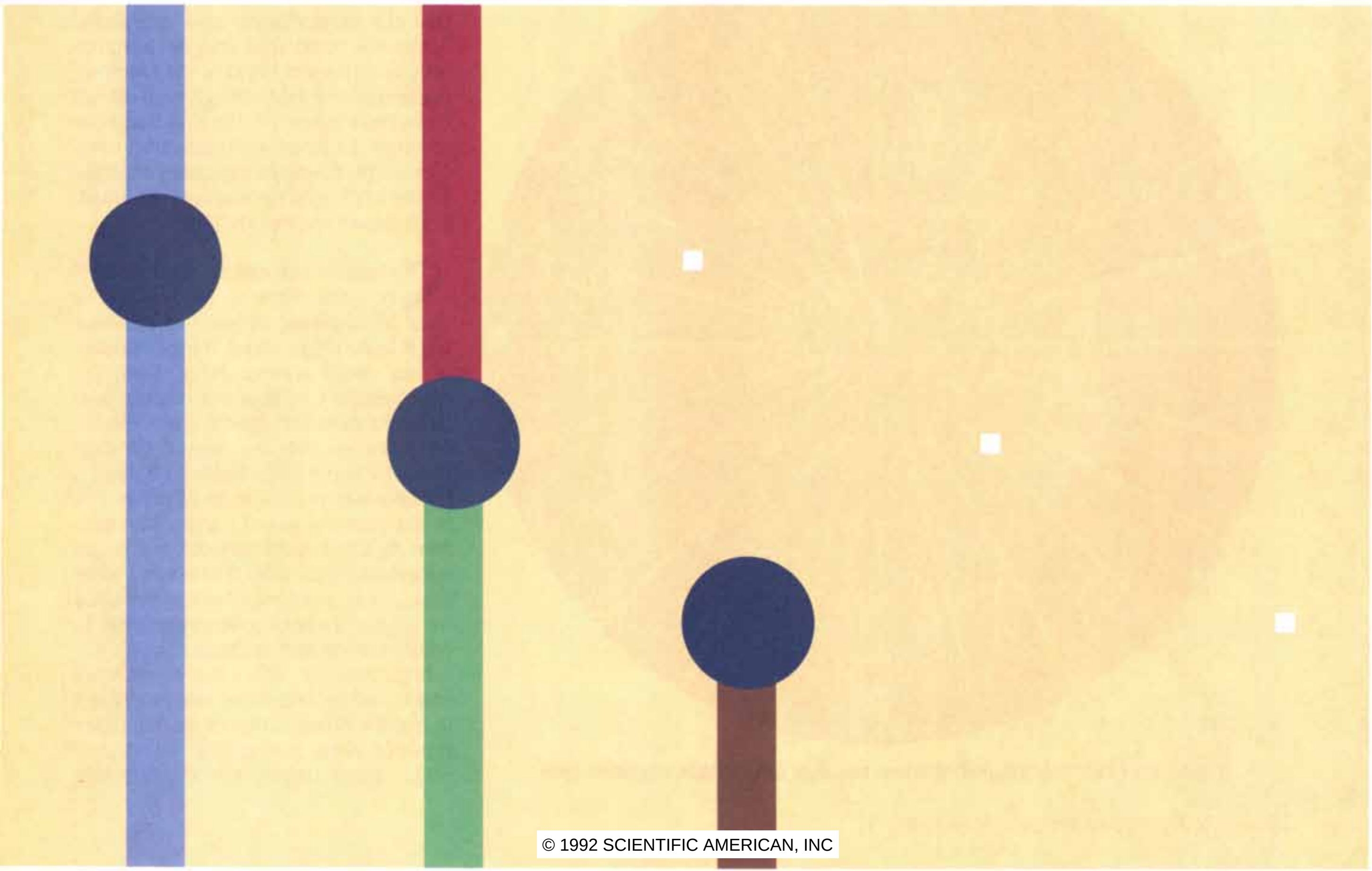
How rich is the perceptual representation in the region corresponding to the blind spot? To answer this question, we asked volunteers to examine a series of simple images. We began with an image in which a line is interrupted by a disk [*see illustration below*]. When a volunteer aimed his blind spot so that it covered the disk, the line appeared continuous in both form and color. Similar observations were made when we displayed a vertical segment that was red on top, green on the bottom and covered by a disk where the segments meet. Subjects reported that when the disk falls in the blind spot, the line appears continuous even though, paradoxically, they could not actually see the border between the green and red segments. The paradox arises presumably because part of the visual system is signaling that the line is continuous while another part is unable to discern a border between the red and green colors.

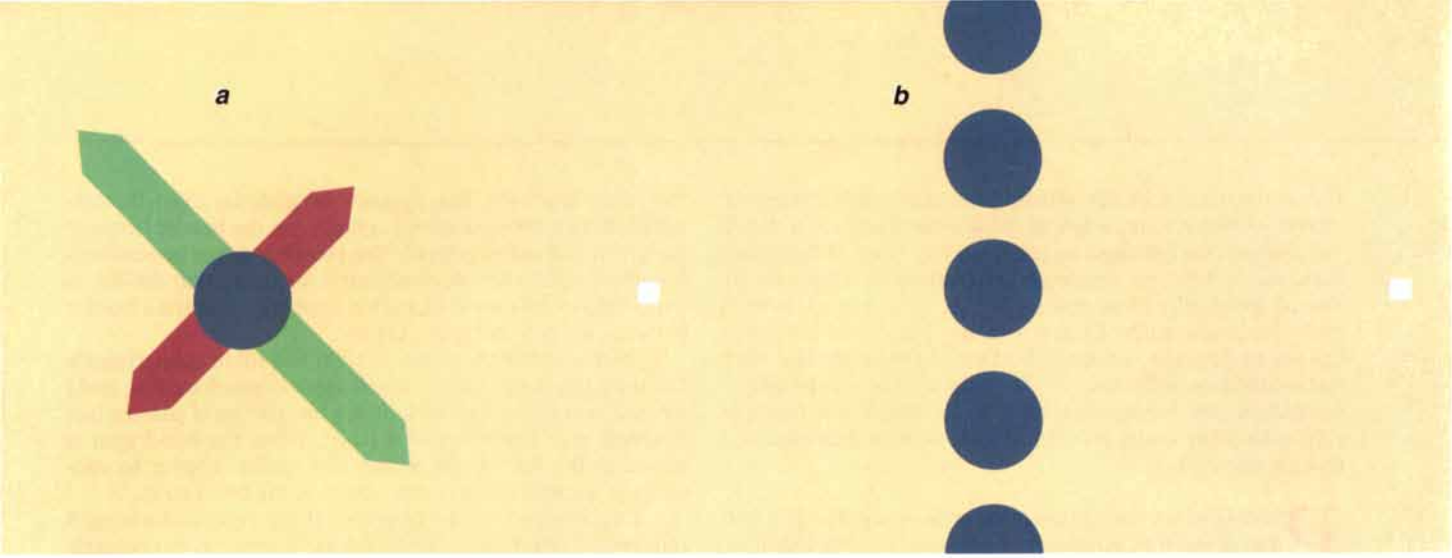
To test whether the visual system will fill in more complicated patterns, my wife, Diane Rogers-Ramachandran, and I devised several figures, including a bicycle wheel pattern [*see illustration at bottom of next page*]. When the blind spot is aimed at the hub of the wheel, the spokes appear to converge at a single point in the center of the blind spot.

A similar effect can be observed if the center of a large X falls on the blind spot. The X appears complete. But remarkably, if one of the segments that make up the X is longer than the other, only the longer segment appears complete [*see illustration at top of next page*]. This result suggests that the filling-in process can be influenced by visual stimuli quite distant from the blind spot.

We were also able to show that filling in is not "cognitive," that is, it is not based on expectations of what things ought to

DISK (*opposite page*) will disappear if it is positioned within your blind spot. Shut your right eye, and hold the page about a foot away from your face. Focus your gaze on the square and at the same time slowly move the illustration toward your eye. At some point, the disk will disappear and will be filled in with the background color. If the disks below fall within your blind spot, they, too, will be filled in. The leftmost line will appear complete. The middle line will also appear continuous, but the color of the line in the filled-in region should not be discernible. In the rightmost figure, the line segment will not protrude into the blind spot.





FILLING-IN PROCESS associated with the blind spot is a sophisticated visual function. If the blind spot falls on the center of a cross (*a*), only the longer segment appears complete. For a pattern of dots (*b*), the dot positioned within the blind spot simply disappears into the background. In illustration *c* the vertical and horizontal segments are misaligned, but when the disk is positioned within the blind spot, the vertical line looks continuous and straight, and the horizontal line looks staggered. This effect was first noticed by Jerome Lettvin and his colleagues at Rutgers University. Motion also influences perceptions that are associated with the blind spot. If you flip back and forth between illustration *d* and the one at the top of page 91, the line will appear to move diagonally. But if you aim your blind spot at the gap and then flip be-

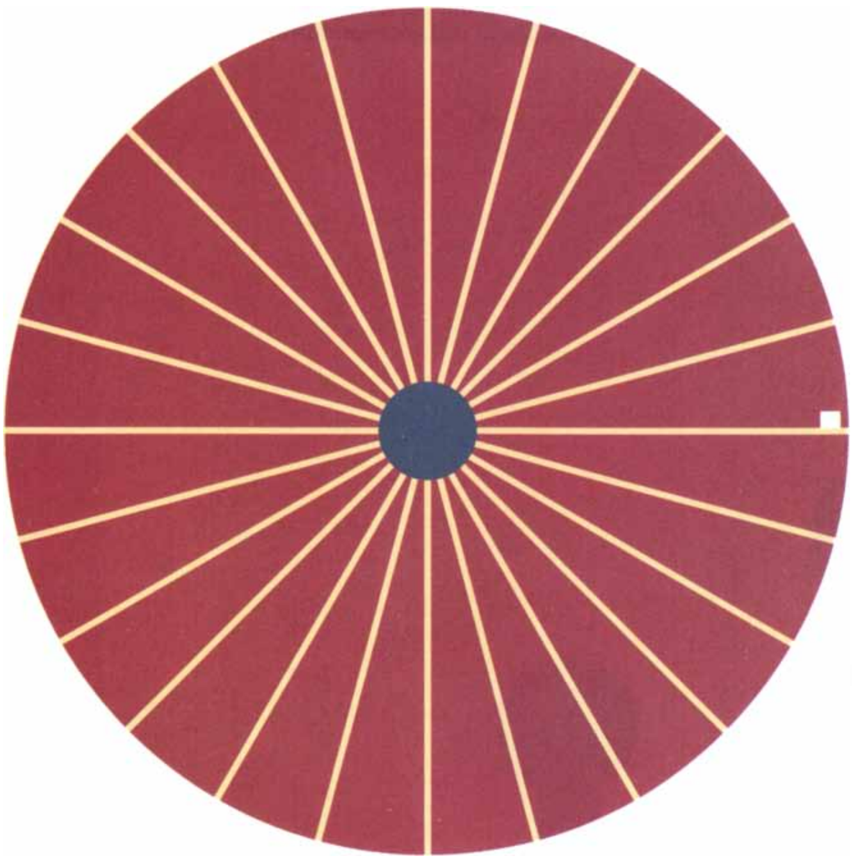
look like. For example, we generated an image that consisted of a vertical column of large spots, one of which was positioned inside the blind spot [*see illustration above*]. All subjects saw the spot vanish; they did not "hallucinate" the missing spot in order to preserve the pattern.

One of the most interesting insights came when we experimented with illusory contours. The visual system produces these contours when the eye records certain sets of incomplete shapes or broken lines. For example, we generated an image consisting of several horizontal lines on a colored background [*see illustration on next page*]. Each line had a small gap about a third of the way from one end. The visual system does not interpret the image simply as several broken lines; instead it produces two illusory contours defining a vertical strip.

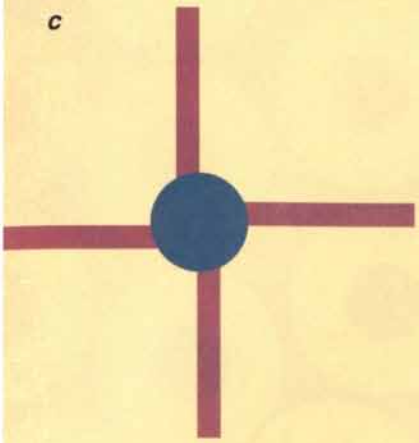
When we asked volunteers to position their blind spot on a break in one of the horizontal lines, most reported that the vertical strip was completed across the blind spot, and the horizontal line remained broken. Yet when we presented the same image with all but three lines removed, the line that runs through the blind spot appeared complete. The filling-in process therefore seems to depend on whether the illusory contours are well defined.

Scientists can deduce the basics of how the filling-in process works by applying decades of accumulated knowledge about the physiology of the visual system. First of all, the light-sensitive cells of the retina translate light intensity and color into electrical impulses that are relayed through the optic nerve to the brain. Specifically, the impulses reach a sheet of nerve cells in the primary visual cortex. The neurons in this region sort out the visual information and relay it to several other areas. Each area seems to be specialized for a type of visual processing, such as color, motion and perhaps shape.

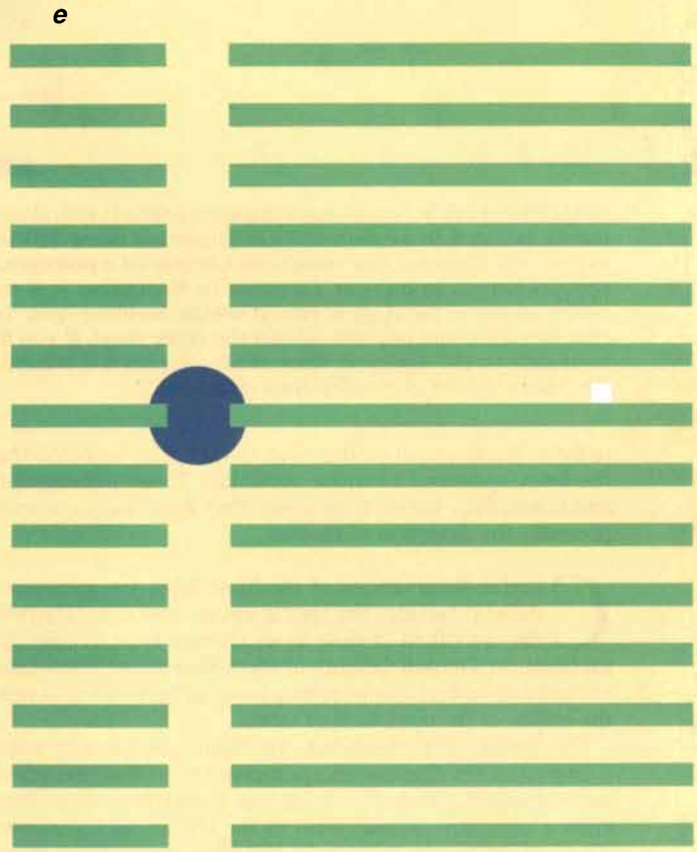
Beginning in 1987, my co-workers and I tried to determine whether filling in occurs before, after or during other types of visual processing. We started with a rather simple type of processing

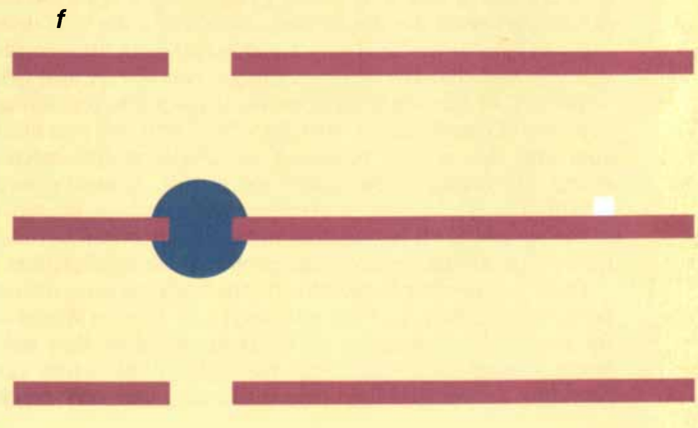


WHEEL PATTERN is completed when the disk falls within the blind spot.



tween the pages, the line will only move vertically. In illustration *e*, the subjective contours give the illusion of a vertical strip between several horizontal lines. The vertical strip appears continuous when the disk is positioned within the blind spot. If the vertical strip is not well defined (*f*), the horizontal line that falls within the blind spot will be filled in rather than the vertical strip.





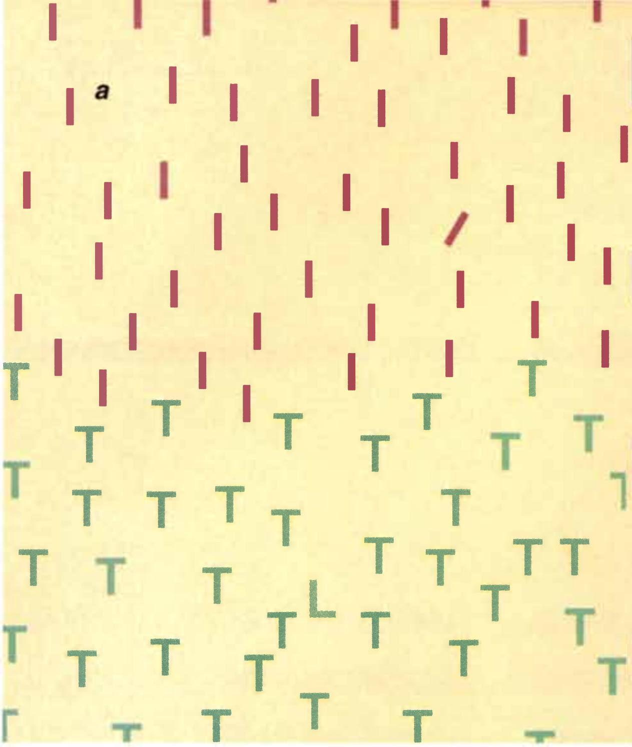
that generates a perceptual effect known as pop-out. The visual system tends to direct attention to certain so-called elementary features in the visual environment. These features appear conspicuous when displayed next to many distracting forms that differ from the targets in such characteristics as color or orientation. Indeed, some psychologists have suggested that pop-out can occur only for features extracted relatively early in visual processing.

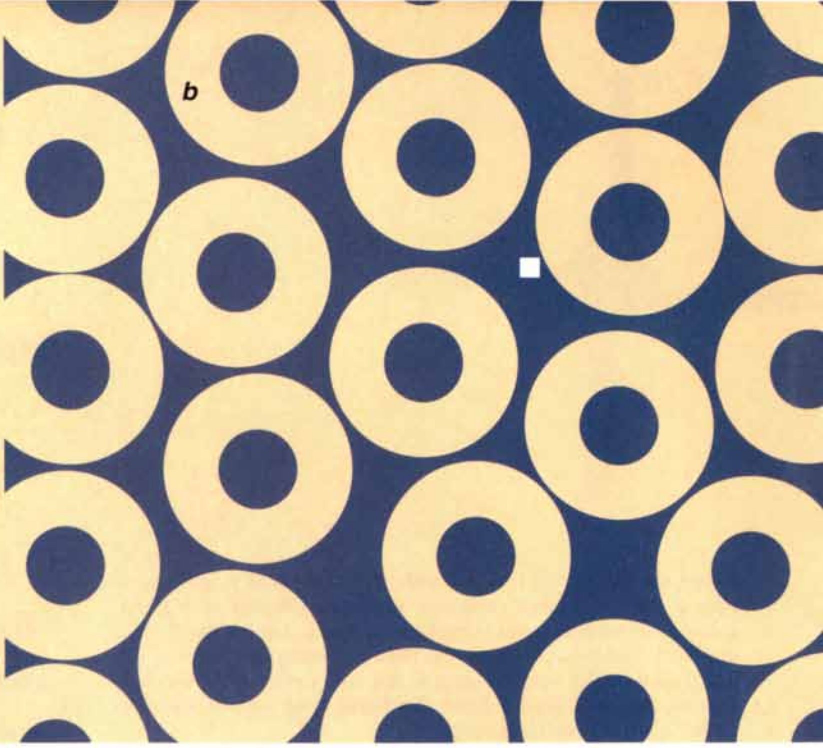
My collaborators and I wondered whether filling in occurs before or after the process that produces pop-out. To explore this, we generated an image consisting of several rings and asked the volunteers to place the center of one of the rings in their blind spots [*see illustration on next page*]. Interestingly, the subjects commented that the ring surrounding their blind spots was filled in and was transformed into a homogeneous disk. They also noted that the disk stood out among the other rings.

This observation has two important implications. First, the filling-in process must occur quite early in visual processing since it actually precedes pop-out. And second, filling in must involve the generation of a perceptual representation. If no such representation was formed, the subjects would not experience pop-out.

William Aiken and I then examined the relation between filling in and motion detection, which occurs during the earliest stages of visual processing. We exploited a familiar illusion known as apparent motion. If two identical parallel lines are displayed rapidly one after the other, for example, the brain tends to perceive a single line in motion. Indeed, apparent motion is the illusion that allows us to perceive continuous movement when a series of images is flashed on a movie screen.

For our experiments, we devised two images, each containing a line interrupted by a small gap [*see illustrations at top right corner of this page and page 91*]. We positioned the gaps in such a way that when the images were displayed in rapid succession, the gap appeared to move diagonally. To start, we presented a subject with the first image and asked him to aim his blind spot at the gap. When the individual commented that the line appeared complete, we switched it off and flashed the second shifted image. We had expected that if filling in followed motion detection, the subjects would con-





DIAGONAL LINE is conspicuous among a field of vertical segments, but an L in a group of Ts is somewhat more difficult to find. The diagonal line stands out because of a perceptual process known as pop-out. Likewise, in illustration *b*, if the center of one of the rings is placed within the blind spot, the ring will fill in and pop out against the other rings. If you fix your gaze on the square in illustration *c* for several seconds, the colors will fill in the disk from either side.

tinue to see diagonal motion. But, in fact, they reported that the lines appeared to move vertically. These experiments and others have led us to conclude that the filling-in process precedes the detection of motion.

Careful observations of the blind spot are sometimes difficult because the spot is always at the periphery of the eye's field of view. In an attempt to overcome this problem, Sir Richard Gregory of the University of Bristol and I found a harmless way to induce an artificial blind spot near the center of the eye's field of view.

The reader can perform our experiments at home by using a television set. Choose an open channel so that the television produces "snow," a twinkling pattern of dots. Then stick a very tiny circular label in the middle of the screen. About eight centimeters from the label, tape on a square piece of gray paper whose sides are one centimeter and whose luminance roughly matches the gray in the snow. To produce the same visual effect, Gregory and I used a computer to generate the shapes and a twinkling pattern of dots.

If you gaze at the label very steadily for about 10 seconds, you will find that the square vanishes completely and gets "replaced" by the twinkling dots. We suspect that this filling-in process is analogous to that associated with the true blind spot and that it may be based on similar neural mechanisms. The fading of the square is probably caused by overstimulation and fatigue of neurons that signal the presence of the square. Such fading does not normally occur, because the eye usually moves around, preventing overstimulation.

These results are consistent with physiological experiments performed recently by Charles Gilbert and Torsten Wiesel of the Rockefeller University. By studying primates, they have made a remarkable discovery: the cells of the retina surrounding a damaged light-insensitive area can very quickly start influencing the primary visual cortex in the region associated with that same area. This observation—and others made by Ricardo Gatas of the National Institutes of Health and John Kaas of Vanderbilt University—might explain the filling-in process that we observed.

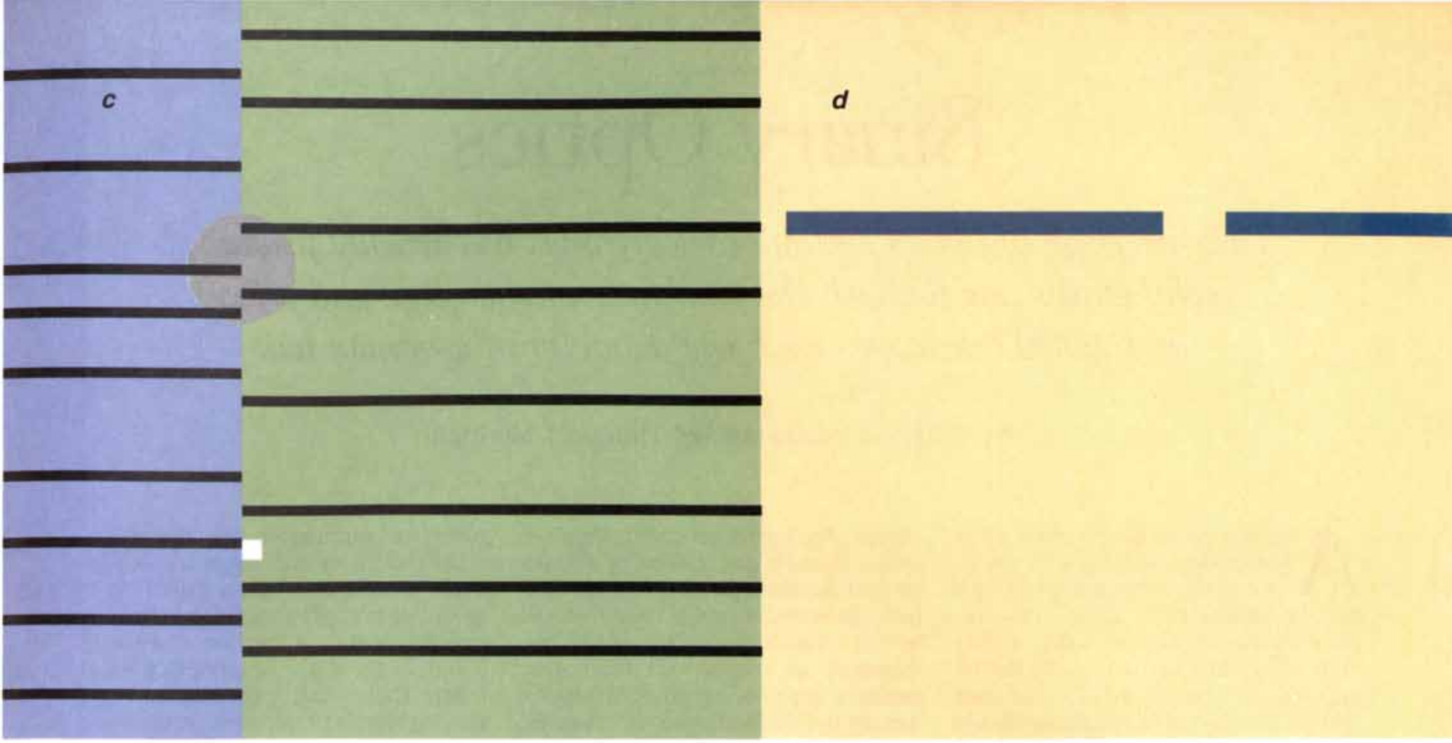
Recently we came up with an interesting variation of the original "twinkle" experiment. When a volunteer indicated that the square had been filled in with twinkling dots, we instructed the computer to make the screen uniformly gray. To our surprise, the volunteers reported that they saw a square patch of twinkling dots in the region where the original gray square had been filled in. They saw the patch for as long as 10 seconds.

The observation suggests that a set of neurons actually generates a representation of the region that was filled in with twinkling dots. Furthermore, the evidence implies that the representation can persist even after the surrounding dots have disappeared.

Filling-in effects can also be observed in static, nontwinkling patterns. For example, color borders tend to fade when the subject fixates on a particular image. (This has been studied intensively by A. L. Yarbus of the Russian Academy of Sciences in Moscow and Thomas Piantanida of SRI International.) My son, Chandramani Ramachandran, and I experimented with a pattern in which a gray disk straddles a vertical boundary between two colors, green and blue, of equal luminance. We asked subjects to gaze at the disk for several seconds. They reported that the disk was filled in with the two colors, but they could not make out a border between the colors. Instead they saw a diffuse, nebulous haze.

Next we altered the image somewhat by adding several black horizontal segments [*see illustration on opposite page*]. Our intention was to create an illusory contour that coincided with the color border. After the subjects gazed at the pattern for a few seconds, the colors filled in the disk from the two sides. But unlike the previous experiment, they formed a crisp color border along the illusory contour. This result is surprising because most vision researchers have assumed that the filling-in process depends only on such simple factors as the presence of edges defined by changes in luminance.

During the past year, we have begun investigations of one of the most interesting kinds of blind spots. If a person injures a tiny area of the visual cortex because of an accident,



illness or surgery, he may have a scotoma, that is, he may be blind in a small section of the visual field.

A person is often completely unaware of a scotoma. If she gazes at a pattern on wallpaper, for example, she does not perceive her scotoma as a change in color or a break in the pattern. Indeed, the design will appear uniform. Yet if a disk of any color or pattern is pasted against the wallpaper in the area corresponding to the scotoma, the individual will not notice the disk and will continue to see only the wallpaper.

My colleagues and I examined two patients who had scotomas near the center of their field of view. (Hanna Damasio and Leah Levi assisted us by proving that the visual areas in the brain were indeed damaged in these patients.) We first presented the patients with a large circle so that it partially overlapped their scotoma. They reported that after about eight seconds the obscured part of the circle emerged, completing the figure. This effect contrasts sharply with similar experiments done on the natural blind spot. When a part of the circle fell within the blind spot, it did not fill in.

Why is there a difference? Most cells in the undamaged visual cortex receive input from retinal cells of both eyes, but the cortex contains a patch of neurons that corresponds to the left blind spot and that receives signals only from the right eye. (A similar arrangement exists for the right blind spot.) Therefore, if a circle falls partially within the blind spot of, say, the left eye, the right eye can usually compensate by signaling the presence of the part of the circle invisible to the left eye. The visual system perceives a complete circle. But if the right eye is shut, it does not signal the presence of the obscured piece, and the visual system simply assumes that a piece of the circle is missing.

On the other hand, if the visual cortex is destroyed in some region, it cannot process signals from either eye, and the visual system seems to adapt by filling in the missing piece.

We then generated an image of a vertical line interrupted by a disk. The patients reported that when the scotoma was aimed at the disk, the line was completed, although, curiously, the process took about five seconds. (A delay of this kind is never seen for the natural blind spot.) We then shifted the upper section of the line horizontally so that the parts on either side of the disk were no longer collinear. The patients reported that the lines initially looked misaligned but that they soon started moving horizontally toward each other until they became collinear and connected across the scotoma. They told us that the sensation of movement was very vivid.

We can only guess as to why the lines seem to become collinear. One of the higher visual areas may get a few clues that the segments on either side of the scotoma are part of the same line. When this area does not receive conflicting signals from the primary visual cortex (because it is damaged), the visual system may ultimately interpret the image as a single vertical line.

Finally, Kerrie A. Maddock, Daniel Plummer and I asked one of the patients to look at a television screen that displayed twinkling red dots. At first, the patient said that only the red color filled in his scotoma; after about eight seconds the twinkling red dots seemed to fill in as well. This experiment suggests the visual area responsible for filling in color may be different from the area associated with the filling in of motion. (The visual cortex of monkeys has such distinct areas, as shown by Semir Zeki of the University College, London.)

In time, we hope to elucidate the similarities and differences between scotomas and blind spots. Perhaps we will learn exactly how the filling-in process is related to surface interpolation and where such processes occur.

Some readers may contribute to this research or, at least, continue to experiment with the blind spot. With a little bit of practice, one should be able to aim the blind spot, making any small object disappear. According to folklore, King Charles II of England used this trick to amuse himself. He would visually decapitate his ladies-in-waiting. But I hope readers will find more pleasure in examining their own heads than in obscuring those of others.

FURTHER READING

VISION: A COMPUTATIONAL INVESTIGATION INTO THE HUMAN REPRESENTATION AND PROCESSING OF VISUAL INFORMATION. David Marr. W. H. Freeman and Company, 1982.

EYE AND BRAIN. R. L. Gregory. Princeton University Press, 1990.

PERCEPTUAL FILLING IN OF ARTIFICIALLY INDUCED SCOTOMAS IN HUMAN VISION. V. S. Ramachandran and R. L. Gregory in *Nature*, Vol. 350, No. 6320, pages 699–702; April 25, 1991.

FILLING IN GAPS IN PERCEPTION. V. S. Ramachandran in *Current Directions in Psychological Science* (in press).