an Article from SCIENTIFIC AMERICAN

JUNE, 1986 VOL. 254 NO. 6

The Perception of Apparent Motion

When the motion of an intermittently seen object is ambiguous, the visual system resolves confusion by applying some tricks that reflect a built-in knowledge of properties of the physical world

by Vilayanur S. Ramachandran and Stuart M. Anstis

Producers of motion pictures, television programs and even neon signs have long banked on the fact that human beings have a quirk in their visual system. When it is confronted with a rapid series of still images, the mind can "fill in" the gaps between "frames" and imagine that it sees an object in continuous motion. For instance, a series of neon arrows lighted up in succession are perceived as being a single arrow moving through space. The illusion of continuous motion is called apparent motion to distinguish it from "real" motion, which is perceived when an object moves continuously across a viewer's visual field. When Sir Laurence Olivier appears to be fencing in a film, he is in apparent motion, whereas a person walking across the theater in front of the screen is in real motion.

In the century or so since the motion picture was invented, filmmakers and television workers have learned to create many compelling illusions of motion, but their progress has been furthered mainly by rule-of-thumb empiricism. Psychological research is only now beginning to describe the mechanisms by which the visual system—the retina and the brain—perceives apparent motion.

The starting point of our own investigations was the premise, set forth by Bela Julesz of the AT&T Bell Laboratories and Oliver J. Braddick of the University of Cambridge, that to perceive an intermittently visible object as being in continuous motion the visual system must above all detect what is called correspondence. That is, it must determine which parts of successive images reflect a single object in motion. If each picture differs only slightly from the one before it, the visual system can perceive motion; if successive pictures differ greatly, the illusion of motion will be destroyed.

Our main question, then, was: How does the visual system go about detecting correspondence? One popular view holds that the brain does so by acting like a computer. When an image stimulates the retina, the eye transmits the image to the brain as an array of tiny points of varying brightness. The brain then compares each point to every point in succeeding frames. By means of complex computations the brain finally discerns the one set of matched points composing a single object that has changed its position—has moved. Attempts to build machines that "see" are generally based on this principle.

The scheme seems logical enough when a simple, unambiguous display is presented. For instance, if a small dot is shown in one frame and is followed by an identical dot placed slightly to the right, the visual system will readily identify the dot in the first frame as an object and find it again—displaced—in the second frame [*see top illustration on page 104*].

The scheme becomes problematical, however, when correspondence is to be detected in more intricate displays. For example, suppose two identical dots are shown in vertical alignment on a computer or television screen and are then replaced by congruent dots shifted to the right. In theory the visual system is now confronted with two possible correspondences: the dots in the first frame could be seen to jump horizontally along parallel paths to the right, or they could be seen to jump diagonally, in which case they would have to cross paths. In practice viewers always see the dots moving in parallel, never crossing.

In another display a computer-generated random-dot pattern forms the first image; then a square region is cut out of the middle and shifted horizontally to create the second image [*see bottom illustration on page 104*]. To the unaided eye the second image appears to be identical with the first and to have no separate central square. Now the images are superposed and then alternated rapidly so that the outer dots are in perfect register, or correlate, and so appear to be immobile. The middle region, where the dots are out of register, appears to move: a well-delineated square is perceived to be oscillating from side to side.

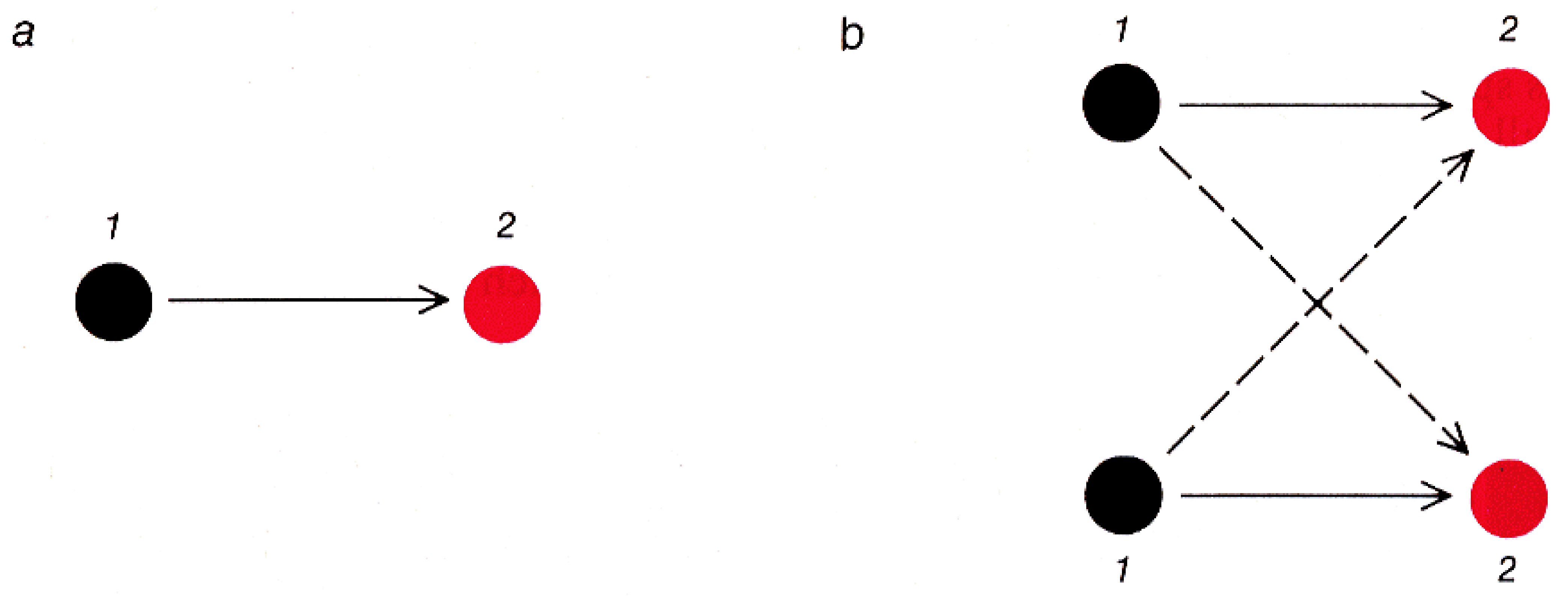
To produce these two illusions by means of point-to-point matchings the brain would somehow need to invalidate hundreds of potential matches, deeming them to be false. While it is possible that the brain laboriously matches all the points and then subjects the matches to a series of elimination tests, our investigation suggests an entirely different approach to detecting correspondence: the visual system applies strategies that limit the number of matches the brain needs to consider and thereby avoids the need for complex point-to-point comparisons.

We believe perception of apparent motion is controlled in the early stage of visual processing by what is in effect a bag of tricks, one the human visual system has acquired through natural selection during millions of years of evolution. Natural selection is inherently opportunistic. It is likely that the visual system adopted the proposed visual short cuts not for their mathematical elegance or aesthetic appeal, as some would suggest, but simply because they worked. (We call this idea the utilitarian theory of perception.) In the real world anything that moves is a potential predator or prey. Hence being able to quickly detect motion and determine what moved, and in what way, is crucial to survival. For example, the ability to see apparent motion between widely separated images may be particularly important when detecting the motion of animals that are seen intermittently, as when they move behind a screen of foliage or a tree trunk.

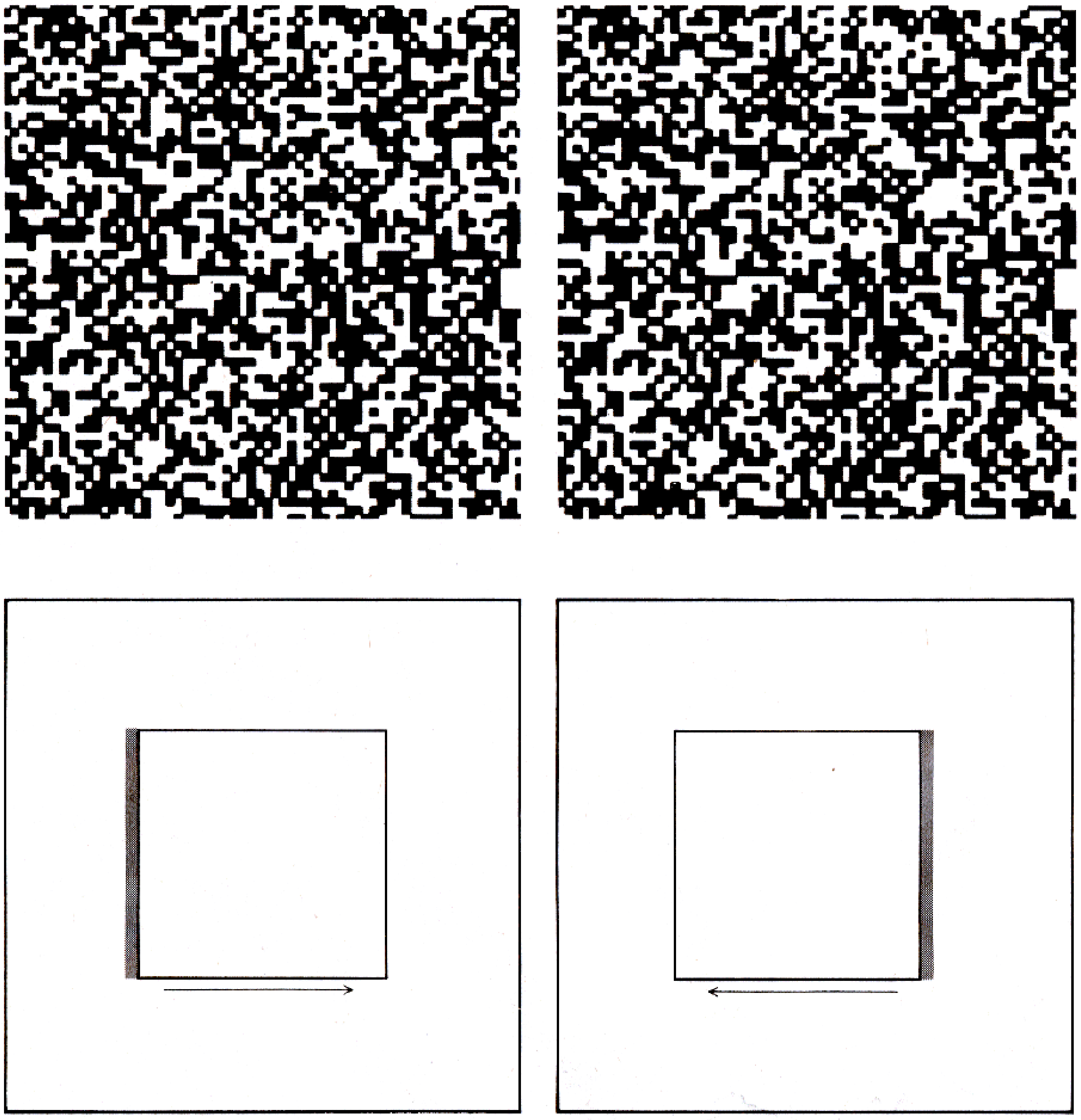
One trick of the visual system is to extract salient features, such as clusters of dots rather than individual dots), from a complex display and then search for just those features in successive images. This significantly reduces the number of potential matches and thus speeds the perceptual process; after all, the probability that two chunks of a visual scene will be similar is much smaller than the probability that two points of brightness will be similar.

Among the features the visual system might attempt to extract from images are sharp outlines and edges or blotches of brightness and darkness; the latter are technically called areas of low spatial frequency. We have evaluated each of these and found that

SUCCESSION OF FRAMES (*top to bottom, left to right*) capture a sneeze. They are from an early motion picture made in Thomas A. Edison's laboratory in about 1890. In order to perceive continuous motion when still images such as these are flashed, the visual system must above all detect correspondence; that is, it must identify elements in successive frames as being a single object in motion.



DOT DISPLAYS that produce the illusion of motion are illustrated. In the simplest possible display (*a*) a single spot of light (*black*) is presented briefly on a computer screen and then is replaced by an identical spot displaced to the right (*color*). Numbers indicate the order of presentation. Rather than seeing two separate dots, the viewer perceives the first dot as moving horizontally (*arrow*). A slightly more complex display (*b*) is ambiguous and can be interpreted in two ways. Two vertically aligned dots (*black*) are flashed and then replaced by an identical pair displaced to the right (*color*). In theory the first dots can appear to move horizontally in parallel (*solid arrows*) or to move diagonally (*broken arrows*). In practice viewers always see the horizontal motion, a finding that raises the question: How does the visual system detect correspondence when it is faced with ambiguity? Evidence indicates that it does so by extracting salient features from images and also limiting "legal" motions to those consistent with certain universal laws of matter and motion.



IMAGES COMPOSED OF RANDOM DOTS are shown (*top*); they produce apparent motion when they are superposed and then flashed alternately. The two computer-generated images are identical except that dots in a square central region of the second image (*right*) are shifted to the left with respect to their position in the first image (*left*), as is schematically shown at the bottom. No central square is visible in either image alone, but when the images are alternated, a central square is seen oscillating horizontally against a stationary background. Computer-generated dot patterns were first introduced by Bela Julesz of AT&T Bell Laboratories and by Donald M. MacKay of the University of Keele in England.

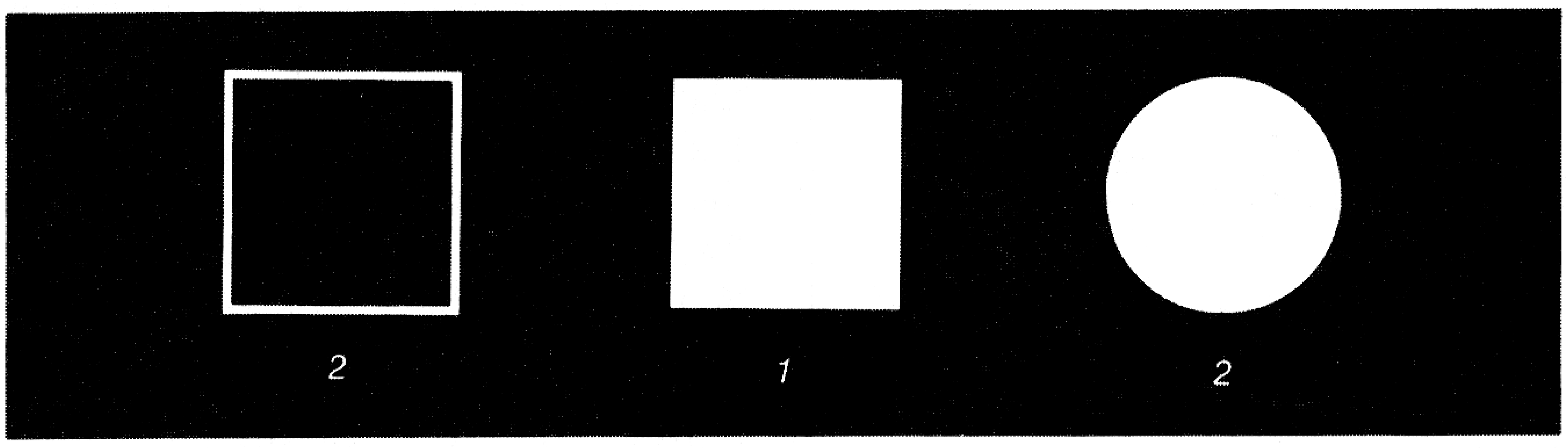
the visual system is likely to detect correspondence between regions of similar low spatial frequencies before it detects more detailed outlines or sharp edges. In other words, the visual system is likely to notice a dark blur moving in a forest long before it identifies the outline of an individual tree swaying in the breeze.

To demonstrate this principle we initially presented a white square on a black background for a tenth of a second and then replaced it with a congruent outline square to the left and a white circle to the right. (All the experiments described in this article presented images to viewers at speeds too fast for thinking; the objective was to eliminate the influence of high-order cognition and focus on the processes responsible for early perception.) Would the viewer see the white square move toward the outline square (which had the same sharp corners as the first square) or toward the circle (which had the same shading as the original square)? Subjects almost always saw the latter effect, providing evidence that the visual system tends to match areas of similar brightness in preference to matching sharp outlines.

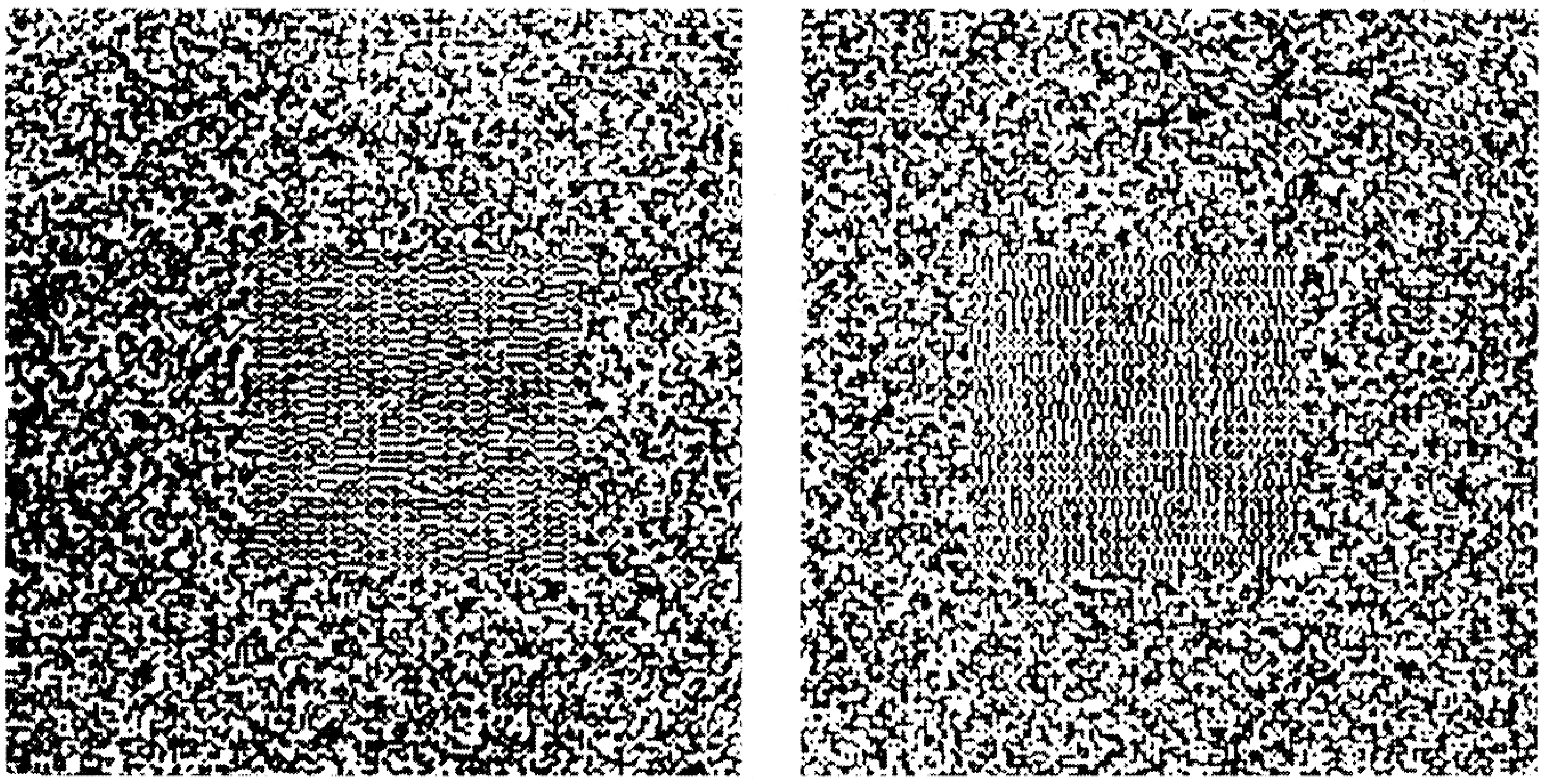
Texture is another feature that appears salient to the visual system. We and our colleagues at Stanley Medical College in Madras, India, presented to subjects two images of random-dot patterns; each image had an inner square with a visual texture different from that of the outer region [*see lower illustration on opposite page*]. The inner square of the second image was the same size and texture as the inner square of the first image, but it was rotated 90 degrees and was shifted horizontally.

We eliminated the possibility that correspondence could be detected on the basis of nontextural cues by ensuring that the dots in the two images would lack point-to-point correlation when the images were superposed and that the average brightness was the same in the inner and outer textures. We could therefore predict that if a shift of texture (such as between the inner and outer regions of the images) is a feature that enables the visual system to detect correspondence, viewers would see the inner square oscillating whenever the two images were alternated rapidly. If, on the other hand, texture is of no help in detecting correspondence, viewers would simply see visual "noise" and no coherent motion. Observers did see the oscillating square, indicating that texture is indeed an important cue for the detection of correspondence by a viewer.

Clearly the mechanism for perceiving apparent motion can accept various inputs for detecting correspondence. We have found a preference for seeing low spatial frequencies and textures; other investigators, such as Shimon Ullman of the Massachusetts Institute of Technology, have found that under certain circumstances line terminations and sharp edges also serve as cues. Perhaps the visual system perceives motion cues hierarchically, first scanning for coarse features before homing in on finer features, rather like an anatomist who first looks through a microscope set at low power before switching to higher magnification. One bit of evidence supporting this view is that subjects do indeed sometimes see the white square in the experiment cited above move toward the outline square, but only when the images are presented slowly and there is time to scrutinize the image.



FEATURES OF OBJECTS that might be extracted to detect correspondence are compared in this experiment. A solid square (*center*) is shown against a dark background and is then replaced with an outline square on the left and a solid circle on the right. The viewer who is confronted with these images usually sees the square move toward the circle rather than toward the outlined square, suggesting that regions of shadow or brightness (low spatial frequencies) are more likely to be detected initially than sharp edges or fine outlines.



TEXTURED DISPLAYS shown here are generated by computer. When they are superposed and alternated, they demonstrate that visual texture can serve as a cue for detecting correspondence. The inner squares, which are shifted horizontally with respect to each other, differ from the outer regions in texture, or distribution of dots, but not in brightness, eliminating the possibility of detecting correspondence on the basis of brightness. In addition the dots in the right-hand image do not correlate with those in the other image, eliminating the possibility of detecting correspondence by point-to-point matching. Therefore the fact that viewers see an inner square oscillate horizontally when the images are alternated can only be explained by the ability of the visual system to detect changes in texture.

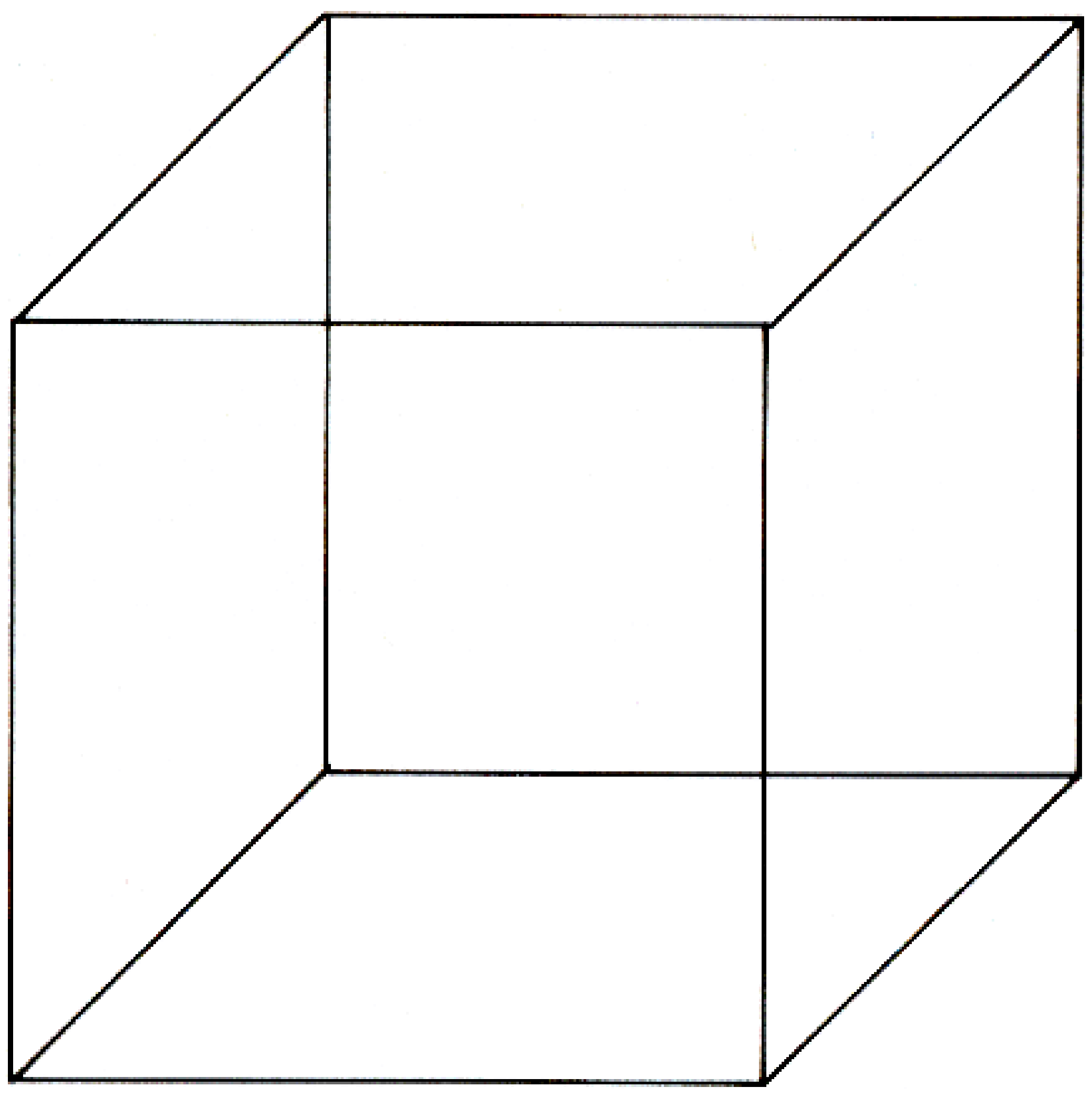
In addition to extracting salient features a second trick of the visual system is to limit the matches it will consider to those yielding perceptions of motion that are sensible, or could occur in the real, three-dimensional world. In other words, as David Marr of M.I.T. first suggested, the visual system assumes the physical world is not a chaotic and amorphous mess, and it capitalizes on the world's predictable physical properties. For instance, if the pairs of jumping dots described above were actually rocks, they would collide if they moved diagonally in the same depth plane and so would fail to reach opposite corners; the only logical perception of the dots' motion is therefore that the two dots in the first frame move in parallel to their positions in the second frame. Sure enough, when these dots are viewed through a stereoscope (a double-lens viewer) and seem to be in separate planes, observers do see them cross; in the real world, objects in different planes—such as airplanes at different altitudes—can indeed cross each other without colliding.

In order to examine the notion that the visual system assumes the world has order, we presented subjects with various motion displays that could be interpreted in more than one way and observed how subjects resolved the ambiguity. We found that one rule applied by the visual system is reminiscent of Isaac Newton's first law of motion, namely that objects in motion tend to continue their motion along a straight path. The visual system perceives linear motion in preference to perceiving abrupt changes of direction.

We demonstrated the power of this rule with an illusion that incorporated a "bistable (dual state) quartet": two dots briefly presented at diagonal corners of a square and then replaced by identical dots at the other two corners. A bistable quartet can be perceived in two ways, somewhat like the familiar Necker cube, which viewers see oscillating between two perspectives. With approximately equal frequency observers of a bistable quartet see two dots oscillating horizontally or two dots oscillating vertically.

The bistable quartet was embedded in the center part of two horizontal rows of dots that appeared to be streaming in opposite directions [*see bottom illustration on next page*]. Only one dot in each row was visible at a time. When the streaming dots reached the center of the screen, the bistable quartet became visible. At that point viewers could in theory see the dots continue in a horizontal path or could see them make a 90-degree turn followed by a second 90-degree turn, to produce two U-shaped trajectories. In practice observers invariably saw horizontal streaming, indicating that the tendency to see linear motion overcame the ability to see the dots in the quartet move vertically. The U-shaped motion was seen only when the parallel rows were brought very close to each other; then Newton's law came in conflict with a competing tendency to see motion between the closest identical points. The proximity principle gains increasing power as objects are moved closer to each other.

A second rule that limits the possibilities for correspondence is that objects are assumed to be rigid; that is,



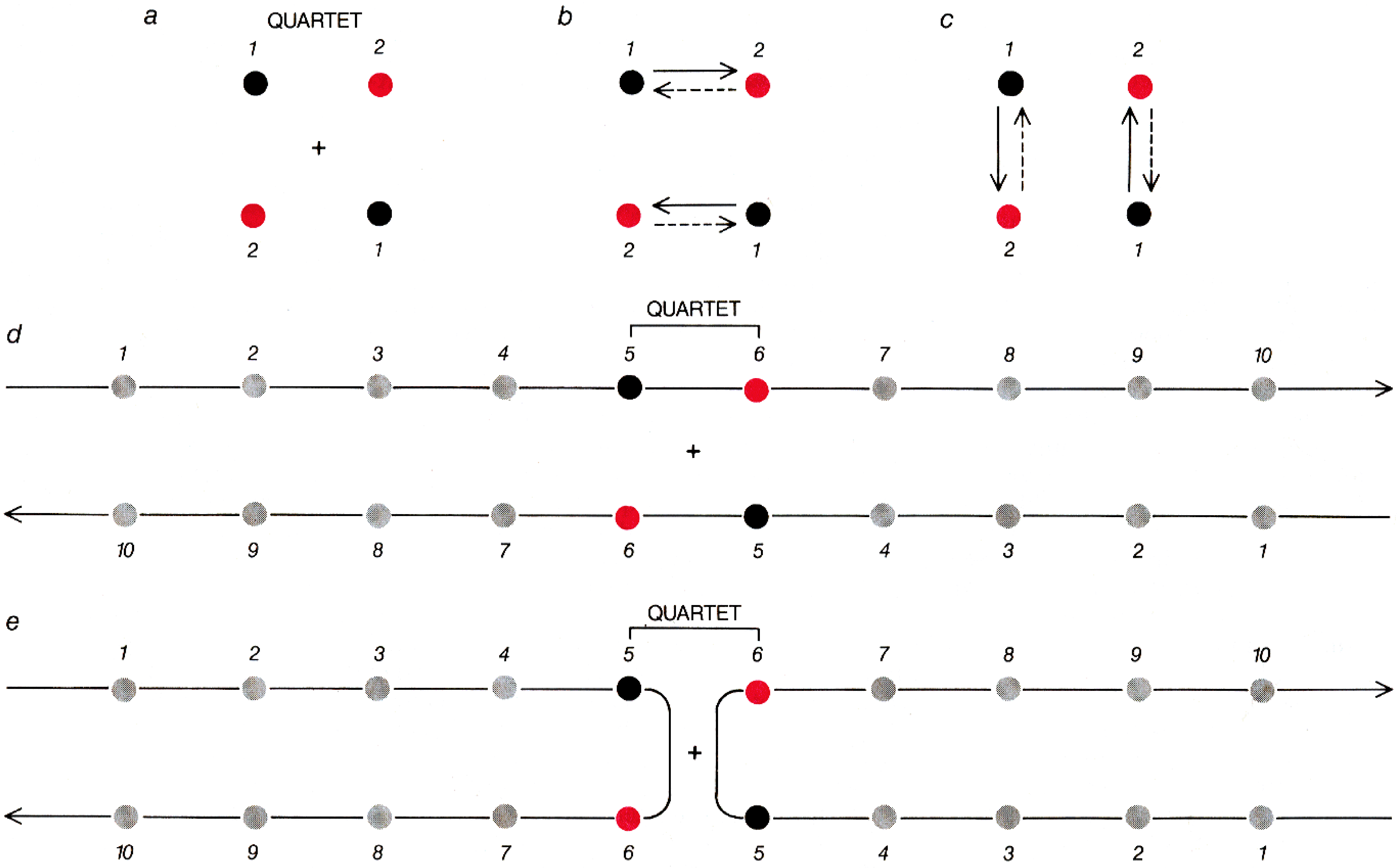
NECKER CUBE, named for the Swiss naturalist Louis A. Necker, can be seen to oscillate between two alternative perspectives.

all points on a moving object are assumed to move in synchrony. Imagine a leopard leaping from a branch of one tree to a branch of another. According to the rule of rigidity, the viewer who picks out any salient feature of the leopard, such as its basic shape (or even the splash of light shading, or low spatial frequency, of its coat), and finds the same feature in a second frame does not need to also compare every black spot on the animal. Without actually perceiving each leopard spot, the person assumes that all spots—indeed, all parts of the leopard—move in synchrony with the salient feature; correspondences suggesting that the leopard's spots can fly off in all directions are not even considered.

An experiment that demonstrated the rule of rigidity involved two uncorrelated random-dot patterns we alternated in a continuous cycle, exposing each picture for half a second [*see top illustration on opposite page*]. Viewers saw random incoherent motion, much like "snow" on an untuned television set. Now we added a narrow strip of dots to the left of and abutting the edge of each image. The "grain" of the dots in the strips was the same as the grain in the images to which they were added, but the strip added to the second image was wider than the strip added to the first one, so that the left margins of the new images did not align. When the images were again alternated, the left margin appeared to shift from side to side. Strikingly, the entire display suddenly seemed to move in synchrony with the margin as a single solid sheet. We call this effect motion capture. Apparently unambiguous motion, such as that seen at the left edge of the images, "captures" ambiguously moving fragments because the visual system tends to presume that all moving parts are fragments of a single object whose surface features move in synchrony.

A further experiment also demonstrated the phenomenon of captured motion, and particularly the ability of low spatial frequencies to effect such capture. We superposed blurred vertical bars of low-contrast lightness and darkness, called sine-wave gratings, on a pair of alternating and uncorrelated random-dot patterns [*see bottom illustration on opposite page*], so that ripple-like shadows seemed to move smoothly across the pattern. The moving shadows caused all the dots in the display to appear to move as a uniform sheet in step with the shadows.

The phenomenon of captured motion now enables us to explain how it is that an oscillating square can emerge



BISTABLE QUARTET, a square matrix of four dots (*a*), is a key component of an experiment demonstrating that the visual system tends to see moving objects follow a straight path. Numbers indicate the order of presentation of dots on a screen; subjects are told to fix their gaze on the central cross. When dots at opposite corners of the quartet (*black*) are flashed and then replaced by identical dots (*color*), viewers are as likely to see the first dots move horizontally (*b*) as they are to see them move vertically (*c*). If two parallel rows of dots (*d, e*) are flashed in sequence (with two of the dots visible at a time), viewers can in theory see one of two trajectories (*arrows*) when the dots in the central, bistable quartet are flashed: horizontal "streaming" (*d*) or vertical "bouncing" along a U-shaped path (*e*). In practice, when the distances between rows and columns of dots are equal, viewers invariably perceive the dots as streaming.

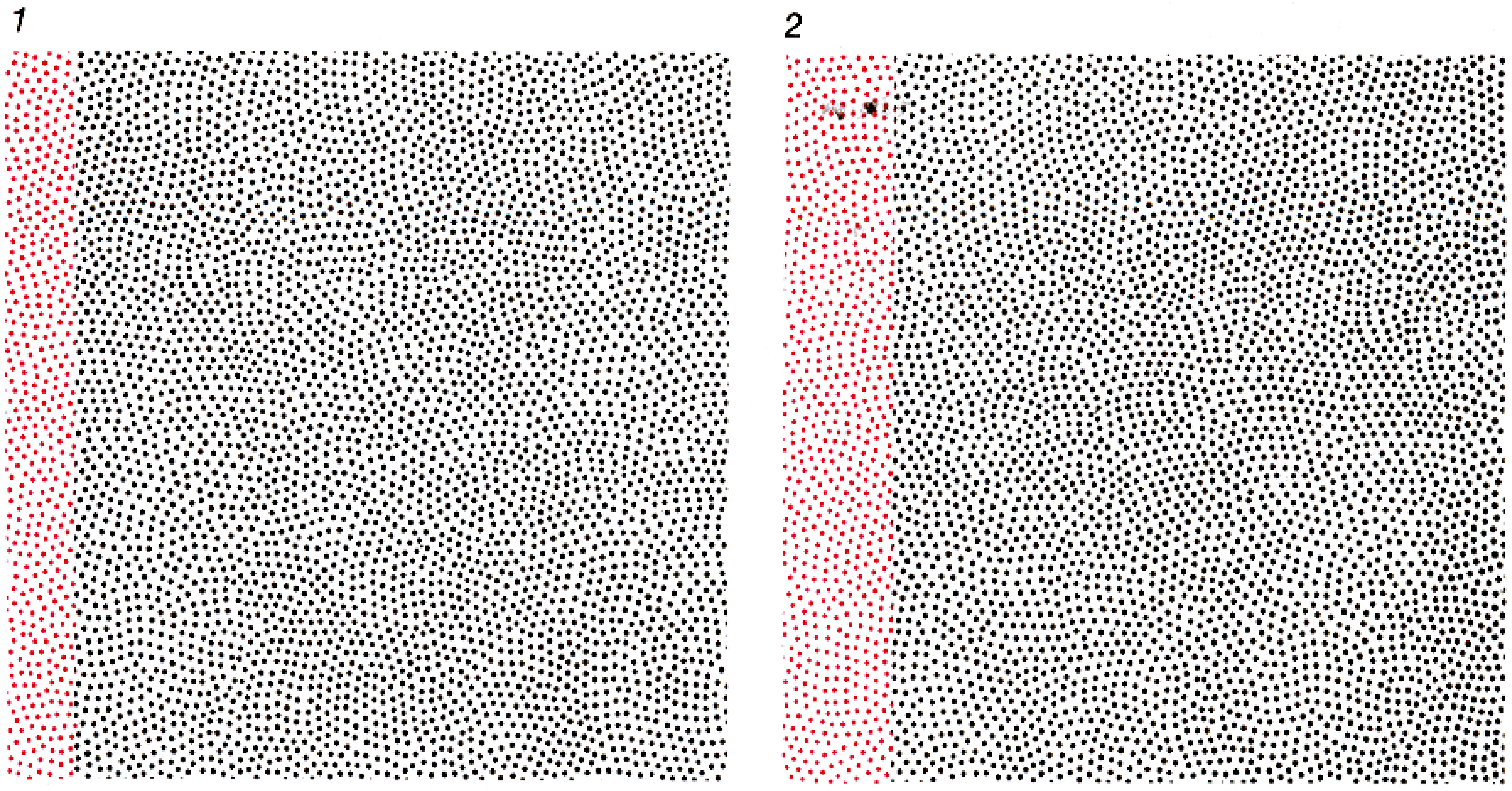
when two images that individually do not appear to include a discrete central square are alternated [*see bottom illustration on page 104*]. Proponents of the computer analogy would contend that the illusion is a product of point-to-point matchings. It seems more plausible to suppose a viewer's visual system extracts a salient cluster of dots from the first display, finds it again in the second display and then assumes that all other "jumping" dots move in synchrony with the salient cluster. Such a short cut would result in faster detection of correspondence than would comparing each point with every other point in successive images. A strategy of this kind would be particularly helpful in the real world, where additional salient features are usually found.

A third rule applied by the visual system, and something of a corollary to the other two, is that a moving object will progressively cover and uncover portions of a background. In other words, when matter, which is normally opaque, temporarily occludes a background, the background still exists; it does not disappear.

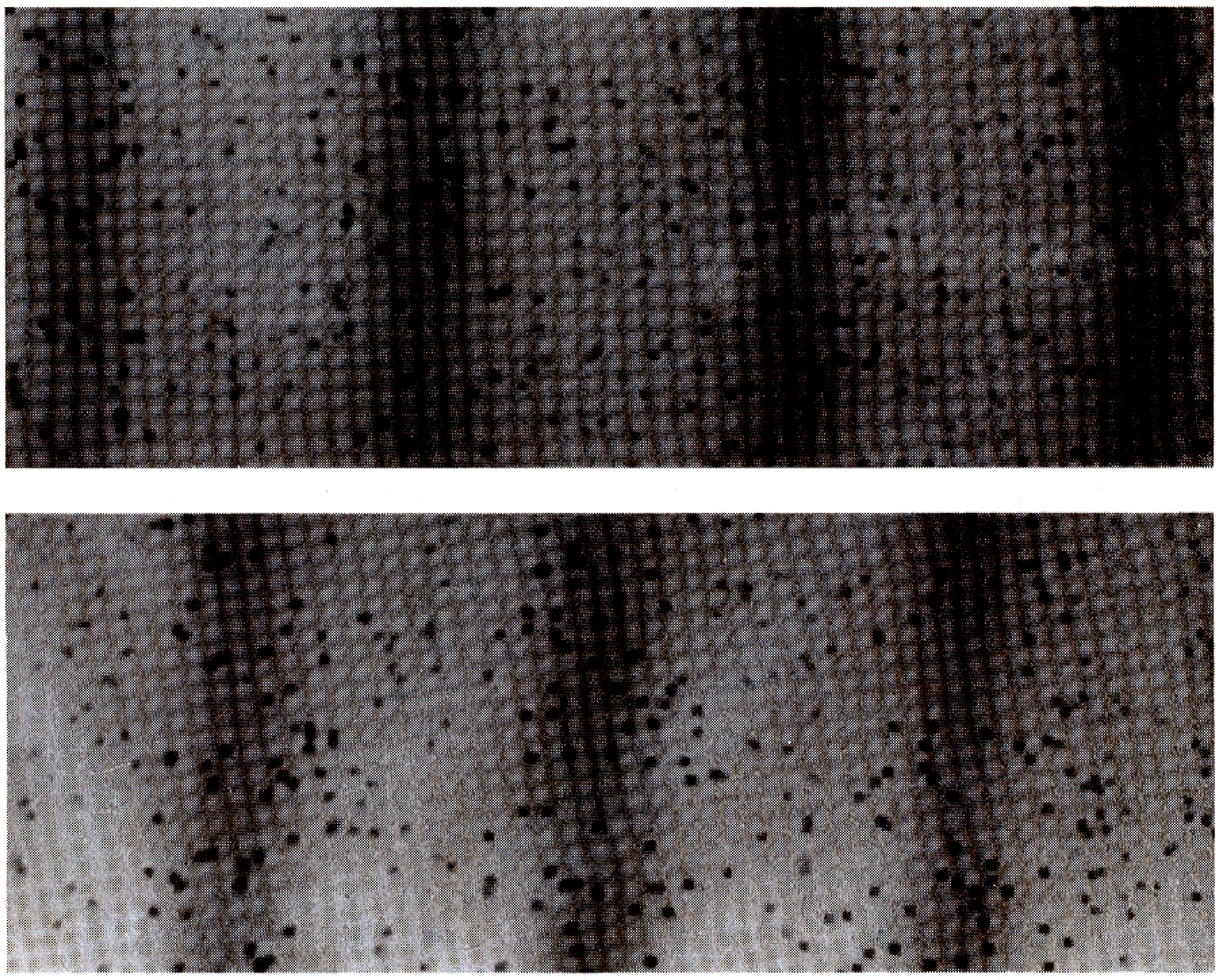
Consider a display in which a triangle and a square below it are presented and then are replaced by another square adjacent to the triangle and directly to its right [*see top illustration on next page*]. One might expect to see the triangle and first square move toward the second square and fuse with it, or to see the first square alone move obliquely toward the second square while the triangle just blinks on and off. In practice one sees something quite different: the triangle appears to move horizontally and to hide behind the obliquely moving square, which now appears to occlude a triangle that is not in fact being displayed. Clearly the brain turns to the real-world property of occlusion to explain the otherwise mysterious disappearance of the triangle. The continued existence of objects is accepted as a given by the visual system, even if the brain sometimes has to invent evidence to fulfill this expectation!

In a related experiment two dots of light in one frame were replaced in the second frame by a single dot, shifted to the right and parallel to the top dot. The images in the first frame seemed to converge at the image in the second frame. On the other hand, when a patch of tape or cardboard was added below the dot in the second frame, a new illusion was produced. Now observers saw the two dots move in parallel, with the bottom one hiding behind the patch, which was perceived to be an occluder. Once again the visual system tended to perceive the motion it was likely to find in the real world.

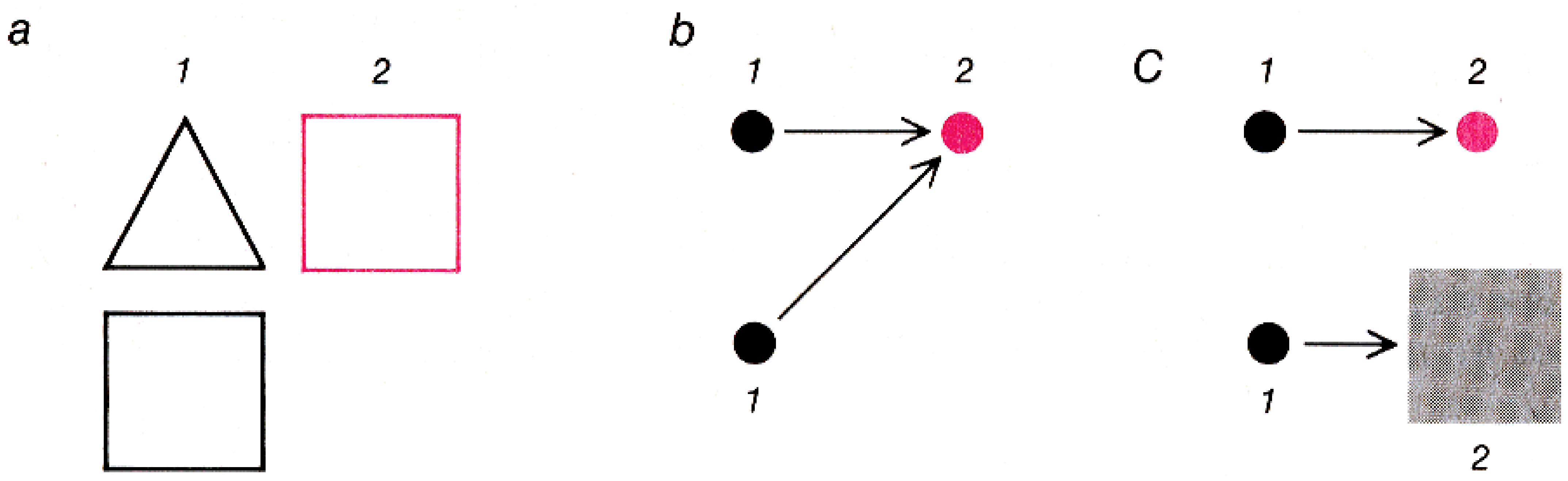
Yet another experiment demonstrated the power of the expectation that one object can occlude another. One of us (Ramachandran) showed viewers an image containing two clusters of four disks each [*see middle illustration on next page*]. In one cluster a pie-shaped wedge was removed from each disk and in the other the disks were complete. We alternated this image with one in which the clusters were transposed. Subjects could in theory see four robotlike shapes, something like those in the game Pac-Man, fac-



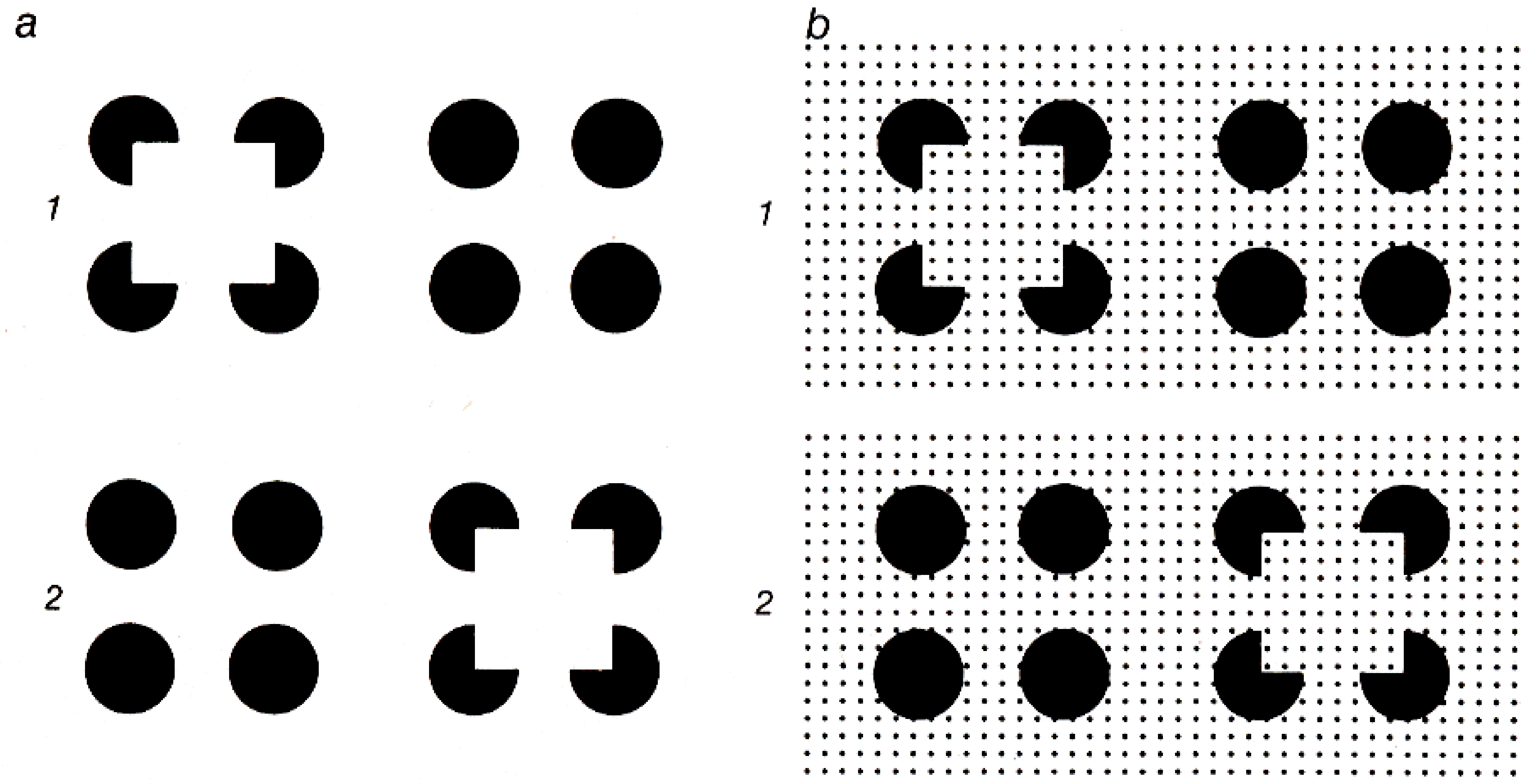
UNCORRELATED RANDOM-DOT PATTERNS form the basis of these displays. When the patterns shown in black are alternated rapidly, viewers see incoherent motion, much like "snow" on a television set. The addition of a strip of dots (*shown in color for clarity*) to the left edge of the images, resulting in these displays, totally changes the perception. The strip in the image at the right (*2*) is wider than the strip in the image at the left (*1*). When the displays are alternated, viewers see the left margin oscillate horizontally and also see the entire display move in synchrony with the margin, a phenomenon known as motion capture. The finding suggests that the visual system tends to see uniform motion and to assume that all parts of an object move in synchrony with any salient part of the object.



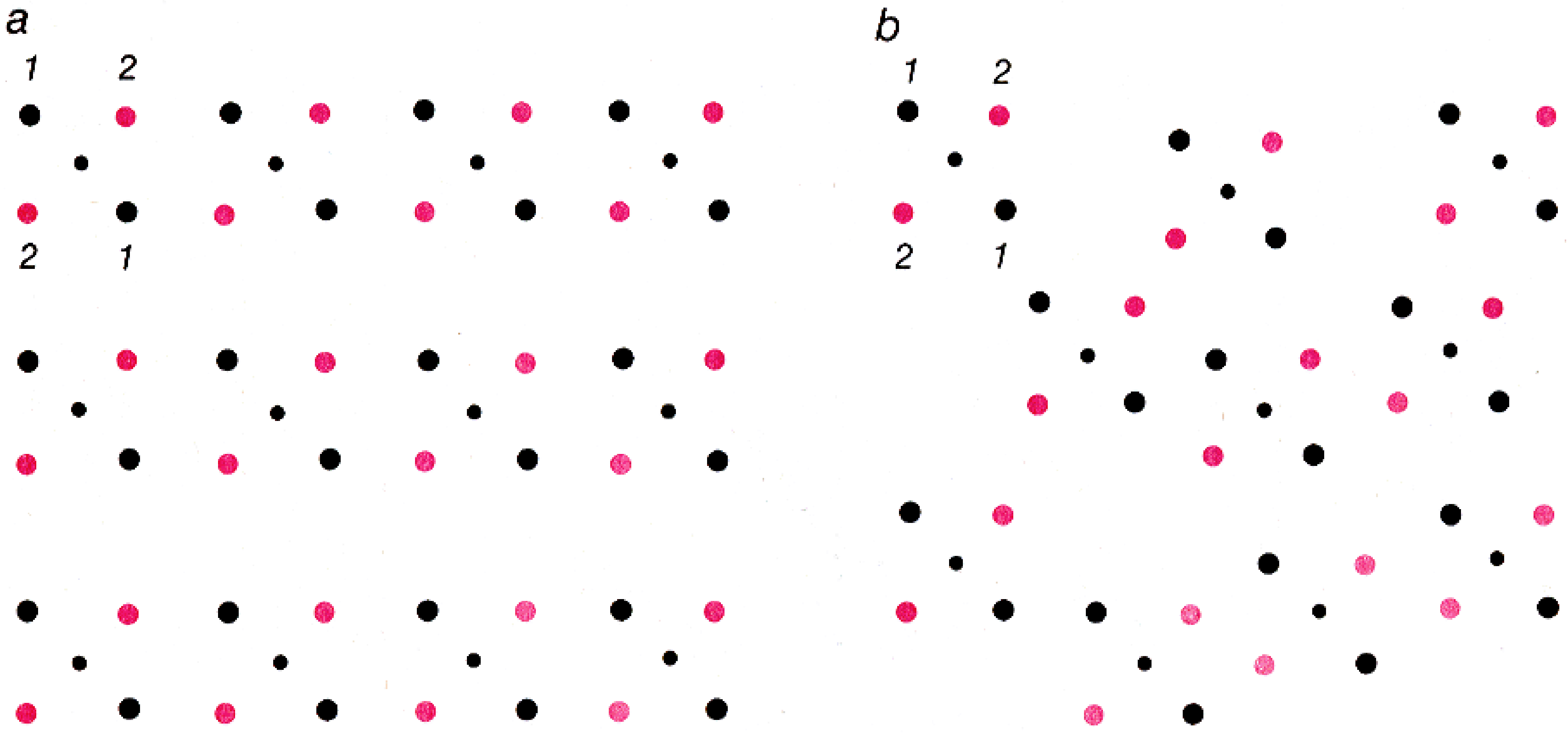
BLURRED LOW-CONTRAST BARS, components of a so-called sine-wave grating, are shown superposed over random-dot displays that produce incoherent motion when they are themselves superposed and alternated in the absence of a grating. The addition of a grating that moves across the screen without ambiguity captures the motion of all the dots and causes them to move with the grating as a single sheet. This effect was studied by one of the authors (Ramachandran) together with Patrick Cavanagh of the University of Montreal.



ILLUSIONS OF OCCLUSION are produced by these images. To explain the mysterious disappearance of an object, the visual system will often assume that the object has been occluded, or hidden, by a larger one. In one experiment (*a*) a triangle and a square are presented simultaneously in one frame (*black*) and are then replaced by a single square displaced to the right (*color*). Numbers indicate the order of presentation. Subjects usually perceive the triangle as "hiding" behind a square that has moved to occlude it. In another experiment (*b*) two spots presented in the first frame (*black*) usually appear to move and fuse with the single spot displaced to the right in the second frame (*color*). If an opaque strip of paper is then pasted on the screen below the second dot, as is shown in image *c*, a new illusion of occlusion results: the lower spot appears to move horizontally and to hide behind the paper occluder. The tendency of viewers to apply the rule of occlusion in resolving perceptual ambiguities has also been emphasized by Irvin Rock of Rutgers University.



DISK-SHAPED IMAGES are elements in computer displays that produce further illusions of occlusion and motion capture. In the images at the left (*a*) pie-shaped wedges are missing from four of eight black disks, first from the cluster of disks at the left (*1*) and then from the cluster at the right (*2*). When the two images are superposed and then alternated, viewers see a white square moving right and left, occluding and uncovering disks in the background, rather than robots opening and closing their mouth. The images at the right (*b*) are identical with the first set but are presented against a background of stationary dots. When these images are alternated, viewers see the dots jump along with the oscillating square.



CLUSTERED BISTABLE QUARTETS are shown. The central dots are fixation points, which are static and continuously visible. When quartets are displayed simultaneously, each quartet is seen to have the same axis of motion (horizontal or vertical) as every other one, regardless of whether the quartets are arranged in regular rows (*a*) or are scattered randomly (*b*). This finding suggests that, in the absence of unambiguous cues to the contrary, the visual system tends to perceive all objects in a given field as moving in the same way.

ing into the center with their "mouths" opening and closing; or viewers could imagine that the white space between the wedges formed a single oscillating square that first partially occluded and then uncovered four disks. It turns out that the visual system interprets the images as an oscillating square, probably because in the three-dimensional world one is more likely to see a square shape occluding a background than to see four identical robots opening and closing their mouths. The property of occlusion overrides any tendency to see movement between the closest similar objects.

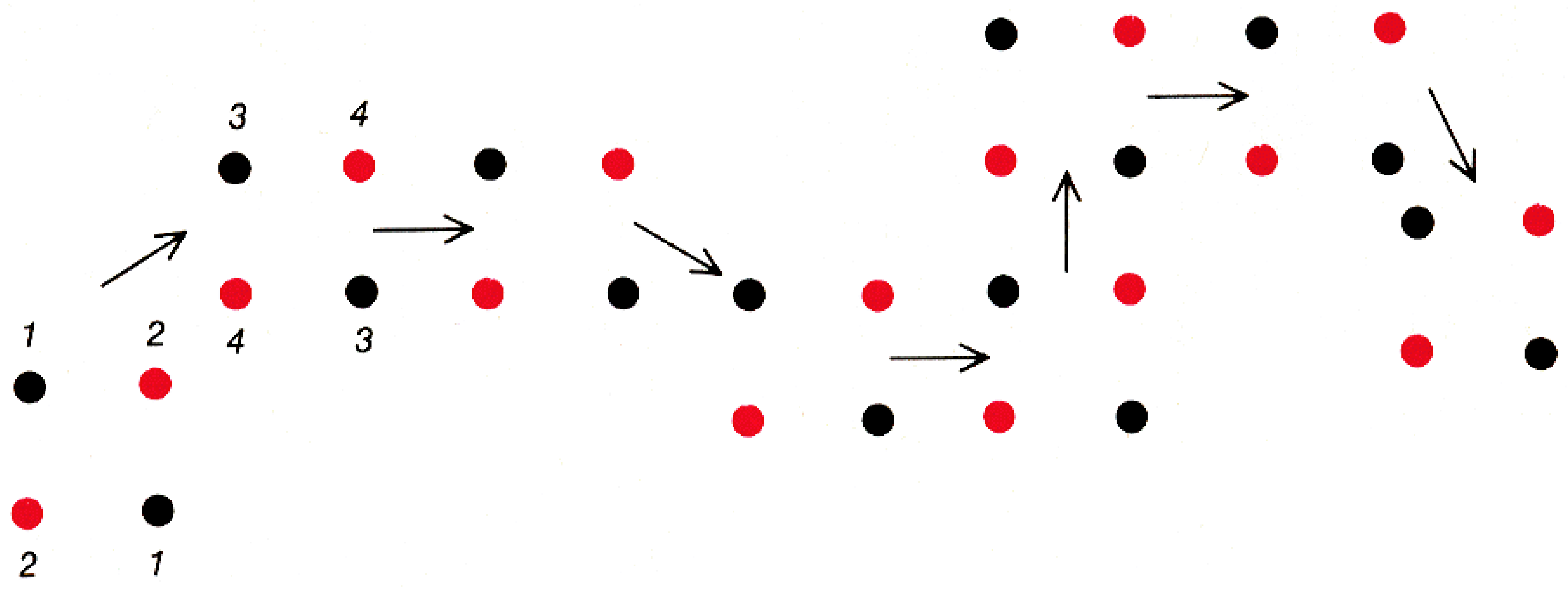
A slightly modified version of this stimulus illustrates the visual system's ability to combine strategies, in this case a predisposition to see both occlusion and rigidity in moving objects. When we superposed the alternating disk images on a background of stationary dots, viewers saw the illusory square oscillate as before, but now they also perceived a sheet of dots oscillating along with the square. The stationary dots were perceived to be a part of the square and therefore were "captured" by its apparent movement. Amazingly, the visual system sees all of this solely as the result of a change in just four tiny pie-shaped wedges.

Having found that the visual system does indeed take short cuts to detect correspondence between images of a single object, we wondered what strategy the system would adopt when faced with many objects in apparent motion. Would it analyze each object independently or would it again take short cuts? Our studies suggest that the visual system tends economically to perceive all objects in a field as moving in the same way unless there are unambiguous cues to the contrary. Gestalt psychologists would call this a tendency to see "global field effects."

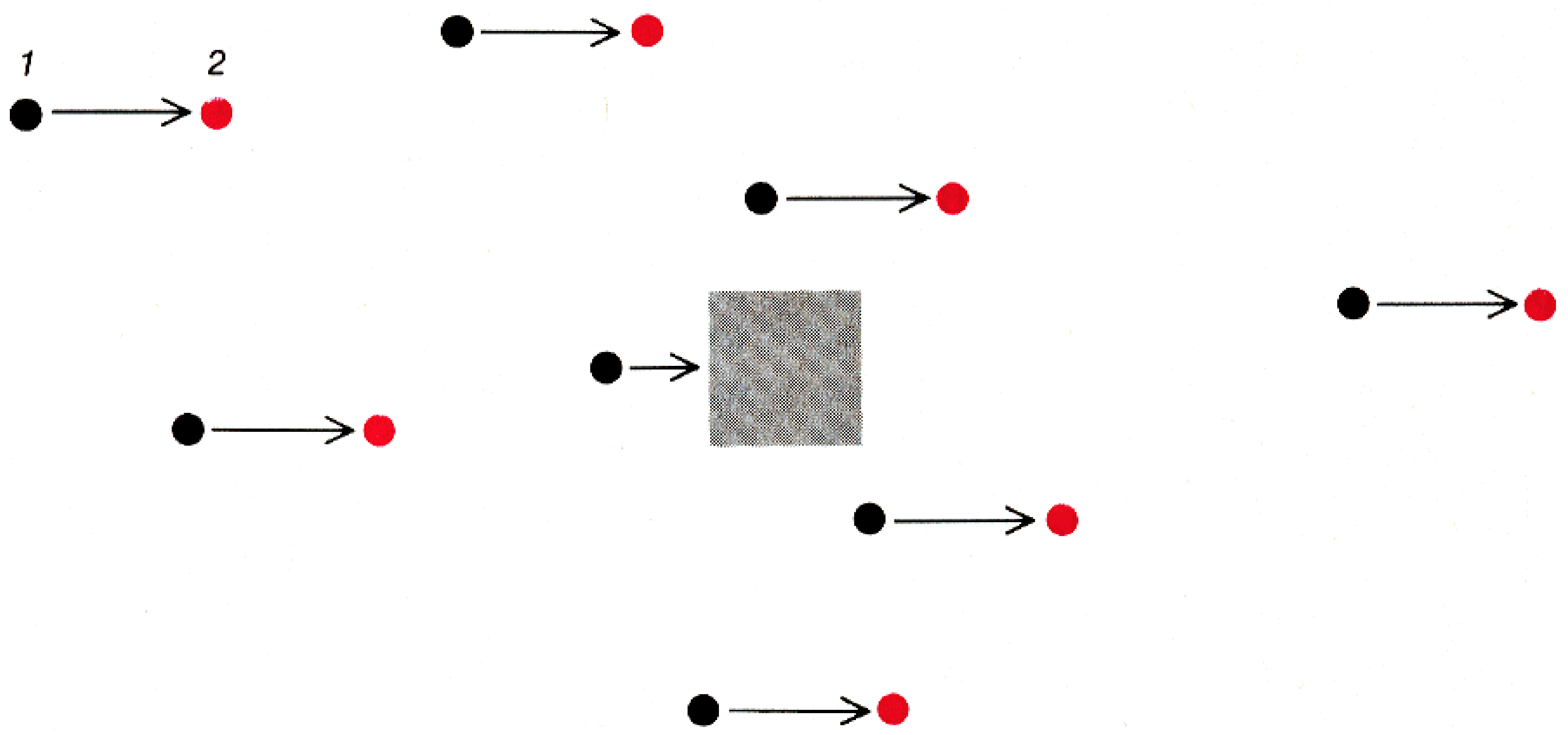
In two related experiments we rapidly and simultaneously displayed many bistable quartets, each of which could be perceived to be in vertical or horizontal oscillation. One experiment had the quartets in three neat rows, whereas the second experiment presented the quartets more randomly. We found that observers perceived all the quartets in each experiment as locking together so that they all had the same axis of motion [*see bottom illustration at left*]. If the visual system did not prefer to see an entire field behave uniformly, and if it processed each quartet independently, our viewers would have seen a mixture of horizontally and vertically oscillating dots.

The unified perception of the clustered quartets suggests that field effects may often be the result of generalizing from a particular instance. That is, the motion seen in one region of a visual field may be significantly influenced by such contextual cues as motion perceived in another part of the field. One way to test this is to cause a bistable quartet to take a "random walk" across the screen [*see upper illustration at right*]. After showing three or four cycles of alternating dots in one bistable quartet, we switched off the display for about half a second before making it reappear elsewhere on the screen. Each of six individuals who viewed the display reported that the motion axis always remained the same even when the square moved to a new location. Once any particular motion axis was seen, the perception apparently acted as a template that created an enduring tendency to perceive similar motion in all other regions.

We recognized that subjects may have interpreted the four-dot display as a single object moving through space. To simplify the test of field effects further, one of us (Ramachandran) alternated images of eight randomly positioned dots with a set of identical dots shifted to the right [*see lower illustration at right*]. Next we masked one of the dots in the second image. Normally when viewers are shown a single dot that is flashed on and off next to an apparent occluder, they see no oscillation. In the context of an array of oscillating dots, however, the perception changed: viewers saw the unpaired dot as oscillating horizontally behind the occluder. They saw what we call entrained motion; that is, motion in one part of the field caused the viewer to see the identical axis of motion in all other parts of the visual field. (The presence of the occluder strengthened the illusion, but the solitary dot also oscillated weakly when no occluder was shown.)



SEVEN QUARTETS that are displayed to subjects sequentially are presented here simultaneously. Arrows indicate the direction of movement from one bistable quartet to the next and numbers indicate the order of presentation of the dots. The dots in color are the ones flashed second in each quartet. Once viewers see the first quartet as having a vertical or a horizontal axis of motion, they almost always see the same axis in quartets presented later and perceive the quartets to be just a single quartet "walking" across the display screen.



RANDOMLY PLACED DOTS are the basis of an illusion studied by one of the authors (Ramachandran) and his student Victor Inada. The display results in a phenomenon known as entrained motion, in which motion seen in part of a field controls the motion seen elsewhere. In a continuous cycle, eight scattered dots (*black*) are flashed on the screen and are then replaced by eight identical dots (*color*) shifted to the right. Viewers see the dots move horizontally (*arrow*). When one dot in the second image is eliminated and replaced with a patch on the display screen (*square*), as is shown here, the partner of the eliminated dot appears to move behind the patch as though it were entrained by the motion in the field.

Our evidence indicates that in perceiving motion a viewer's visual system rapidly extracts salient features and applies built-in laws of motion when processing the features. It also responds to contextual clues in the rest of the field. Of course, even if one believes in the existence of such mechanisms and rejects the concept of laborious point-to-point matchings, an obvious—and much debated—question remains: How does the visual system apply all these strategies? Does it have neurons that are "hard-wired" with the strategies from birth? Or does the perception of motion require some higher level of cognition?

As we mentioned above, the experiments described in this article were designed to eliminate the effects of high-level cognition; specifically, we flashed images at speeds too rapid to allow the brain to make thoughtful decisions about what it was seeing. Our results therefore suggest that low-level processes can, on their own, control the perception of apparent motion during the early stages of visual processing.

Some other evidence also favors this notion over theories requiring the participation of intellect in early, as well as late, stages of motion perception. For instance, an illusion can be seen even when an individual knows an image is an illusion. Neurobiological evidence has been adduced in the past decade by David H. Hubel and Margaret S. Livingstone of the Harvard Medical School, by David C. Van Essen and John M. Allman of the California Institute of Technology and by Semir Zeki of University College London. They have found in monkeys that nerve cells sensitive to the motion of images with low spatial frequencies are distinct from the cells that are sensitive to color, line terminations, angles and other sharp features. This is consistent with our finding that the brain's motion-detecting system pairs off objects sharing low spatial frequencies faster than it pairs off objects sharing sharp features, and it suggests that neuronal activity may be sufficient to account for the initial detection of correspondence by the viewer.

The cellular events that mediate early visual processing in human beings are still very much a mystery, but in time the neurobiological approach should combine with the psychological to elucidate the processes by which the visual system detects correspondence. Our findings suggest, meanwhile, that new advances in the construction of motion-detecting vision machines might be made if investigators who design those machines would attempt to substitute the tricks we have described here for the point-to-point schemes that are currently in vogue.