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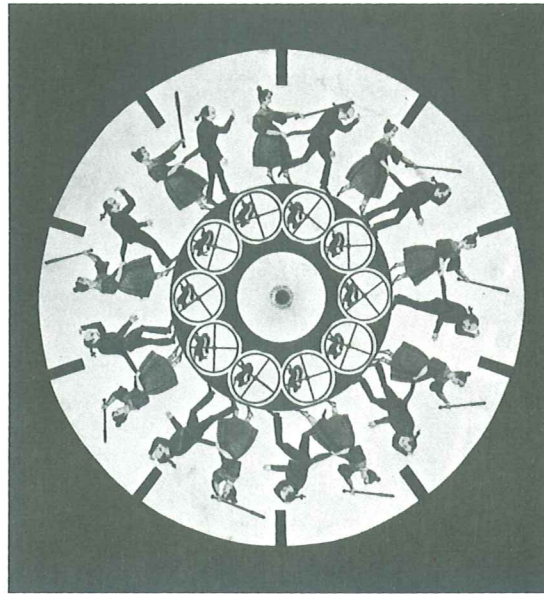
THE PERCEPTION OF MOTION

The moon seems to be sailing through the clouds. Most of us have experienced this illusion, but few ask why it occurs. Of course, the moon does change its position in the sky as the earth rotates, but that movement is too slow to detect with the eye. In fact, we perceive the moon to move in a direction opposite to that of the clouds passing in front of it, regardless of the direction in which the clouds happen to be traveling.

Ever since the discovery in the nineteenth century of illusory stroboscopic effects, the predecessors of moving pictures, motion perception has been one of the major areas of investigation in vision. Like form or color, motion is a perceptual property of objects. Although the second hand and the minute hand of a watch both move, the second hand is seen to be moving whereas the minute hand moves at a rate usually below our threshold for detecting its motion. Although it is the clouds that often move at a rate that we can detect, it is the moon that we perceive as moving. The perception of motion, then, is not simply a reflection of the physics of motion, of what is happening in the world. Although in physics one might say that no object moves absolutely but only changes its position relative to some frame of reference, in perception objects do appear to move absolutely or to be stationary.

Our perception of motion is usually veridical, but sometimes it can be highly deceptive, as is the perception of the moon passing through the clouds. In fact, much of the research in motion perception has been designed to explain this and other illusions of motion. Why, for example, do people and things depicted in motion pictures appear to move? When we look at a single star in an otherwise dark sky, why does it appear to drift? Why does a stationary object sometimes give the fleeting impression that it is moving upward after we have been looking at a waterfall? In this chapter, I will discuss the nature of each of these illusions. But understanding the perception of objects that are really moving turns out

The sequence of photographs of a pole-vaulter in action conveys an impression of motion, although not the perception of motion that one obtains from viewing the successive projections of such a scene on a movie or television screen.



One of the earliest techniques for creating apparent motion. The figures appear to move when the disk is spun in front of a mirror and the figures' reflections are viewed through one of the narrow slits in the disk. Many people believe that the effect is based on the visual persistence of one picture as successive pictures are seen. This explanation, however, would only explain the absence of flicker, not the perception of motion.

to be just as much of a puzzle, and it is well to begin our discussion with those perceptions.

The Perception of Real Motion

If a cat jumps from a chair within our field of vision when we happen to be looking at the newspaper, the cat's image will displace over the retina, and we will perceive its motion. It thus may seem reasonable to suppose that the bases of motion perception are the sensory consequences of a displacing image. The perceptual system must detect the displacement if we are to gain the information that the cat yielding that displacing image is in motion. Physiologists have in fact discovered cells in the retina or in the visual cortex of some animals that discharge rapidly if, and only if, a contour or spot moves over the region of the retina to which such cells are connected. Presumably such cells exist in the human visual system as well. The firing of these cells, which have been called *motion-detector mechanisms*, might be regarded as an explanation of the perception of motion.

There is a problem with this explanation, however. For animals that move their eyes as we do, displacement of contours over the retina is neither necessary nor sufficient for the perception of motion. It is not necessary because we often track a moving object by moving our eyes, thus holding its image more or less stationary on the retina. Nevertheless, we see the object moving. Moreover, in many illusions of motion—the moon in the clouds and the still images in the frames of a movie, for instance—the image of the object seen as moving is stationary. Neither is the displacement of contours over the retina sufficient, because frequently an object's image displaces over the retina without creating an

impression of motion. When we move our eyes across a room, for example, the location of chairs and tables appears unchanged, although the images of them on the retina move. Investigators refer to this phenomenon as *position constancy*.

Instead of regarding these motion-detector mechanisms as the immediate cause of motion perception, at least in animals high on the phylogenetic scale, it may be more appropriate to think of them as a source of information about events on the retina. In interpreting what is happening in the world, the perceptual system must take into account other information from other sources as well. For example, if these detectors signal "motion" when only the eyes are in motion, the perceptual system must discount that signal as a sign of object motion. The perceptual system "assumes" it was caused by the observer's own eye movements. However, if the signal occurs when the eyes are stationary, then it is interpreted as a sign of object motion.

If the detectors do not signal motion, as when we track a moving object and the retinal image remains stationary, the perceptual system can still infer that the object is moving. For this inference to be made, however, the perceptual system must somehow know that the eyes are in motion.

How does the brain "know" whether or not the eyes are moving and, if they are, in what direction and at what speed? Given what is understood about how the brain gains information about movement of other parts of the body, we might suppose that such information derives from sensory feedback. For example, physiologists believe that, when the arm bends, receptor cells in the elbow joint signal the change. Such proprioceptive information has long been held to come from the activity of muscles as well as joints. Receptor cells in the eye muscles were thus assumed to be the source of similar information about eye movement.

It is unlikely, however, that the information that tells us about eye movement derives from sensory feedback. Consider two countercases. First, there are circumstances in which the eyes remain perfectly still—and thus there is no proprioceptive feedback that they are moving—but nonetheless the eyes are interpreted as moving. If the eye muscles are paralyzed or are otherwise prevented from moving, the observer may still attempt to look at an object in the periphery. Each time this happens, the entire visual field appears to move rapidly in the direction of the intended eye movement. Helmholtz and subsequent investigators inferred from this result that the perceptual system treats the intention or command to move the eyes as equivalent to actual eye movement. Ordinarily the command would be followed immediately by eye movement. Thus the image displacement of a stationary thing would not be improperly interpreted as signifying that the object was in motion. But if the eyes cannot move,

the command is still recorded, and the eyes are interpreted as moving. Consequently, the stationary image is incorrectly interpreted as signifying that the object is in motion.

In the second countercase, the eyes are moving—and thus there should be proprioceptive feedback—but they are nonetheless treated by the perceptual system as stationary. If we push our eyes gently to the side with our fingers, presumably there is proprioceptive feedback to that effect, just as there would be if we lifted a limp arm by active movement of the other arm. But we can infer from the fact that the entire scene appears to move that the perceptual system treats such imposed eye movement as no movement at all. Position constancy is not achieved because, with no eye movement registered, the perceptual system does not discount image displacement.

Therefore, it seems that we “know” what our eyes are doing not by what they are in fact doing but by what we command them to do a fraction of a second before they move. The information is efferent (derived from signals flowing *out* to effector organs) rather than afferent (derived from signals flowing *in* from sense organs). Some evidence suggests that a similar mechanism plays a role in the interpretation of other body movements as well.

We have seen that the perceptual system gains information on the displacement of contours (or its lack) over the retina by the firing of motion-detector cells. The perceptual system not only makes use of this information about image motion, but also takes account of information about the movement of the eyes in arriving at an “inference” as to whether or not the object producing such image contours is moving. The general rule of motion perception, it seems, is this: An object that changes its *perceived* direction at a rate fast enough for the brain to detect will generally be seen to be moving, and an object that does not will generally appear to be stationary.

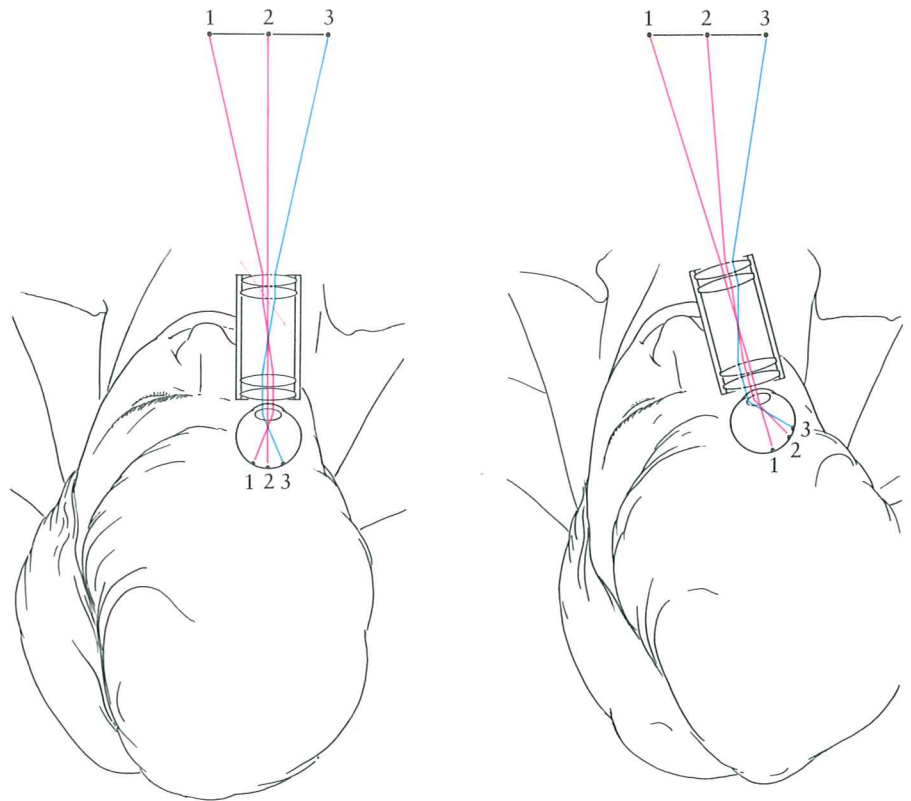
A brief comment should be made about the perception of rates of motion, or velocity. If the perception of motion depends upon detecting a change of perceived direction, the perception of velocity depends upon detecting the rate of change of perceived direction. One might expect that perceived velocity would decline with the object’s distance, because the angular rate of change in direction of an object moving across the field at a constant speed is less the farther away the object is. After all, the farther away the object is, the smaller will be the visual angle traversed by its image per unit of time. Nevertheless, constancy prevails, at least up to a certain distance. The object’s velocity is perceived to be roughly the same whether the object is near or far. The explanation of such constancy is still in dispute, since two possibilities exist: Either we take into account the object’s distance, as when we achieve size constancy, and thus inter-

pret the visual angle traversed per unit of time accordingly, or we judge velocity in terms of the proportion of the extent traversed by an object per unit of time, relative to the object's frame of reference (for example, a mouse will traverse a corridor in the same amount of time whether it is near or far from us).

The Perception of Motion when We Are in Motion

In many instances, we are the ones in motion, not the objects around us. When we move, all objects change their direction with respect to our position. Thus, according to the general rule of motion perception, they ought to appear to move. Instead, however, our perceptual system attributes the change in the direction of things to our own motion. For any given movement of our own, an object at a particular distance will undergo a particular change in its direction and will do so at a particular rate (motion parallax). As long as the object's distance is perceived correctly, it will appear to remain stationary. Thus, position constancy is achieved. For example, an object seen straight ahead and close by will "go" to the observer's left at a fairly rapid rate as the observer moves to the right. Does this mean that, if the object were perceived to change its direction differently or at a different rate with this same movement of the observer, it would appear to move? It is plausible to believe that it would, and in fact we know that it would. Around the turn of the century, George Stratton, a psychologist at the University of California at Berkeley, performed an experiment that is still being discussed and disputed. For eight days in succession, Stratton wore lenses mounted in a tube in front of one of his eyes that inverted and reversed the images that reached his retina. He was interested in discovering whether or not the scene that appeared upside down would eventually appear right side up if he continued to wear the lenses, an issue we will take up in Chapter 8. What is of interest here is Stratton's observation that objects viewed through the lenses appeared to shift in direction in an abnormal way when he moved. At first, a stationary scene appeared to move in the direction of his own movement and at a faster rate. We can conclude from this fact that, when there is an abnormal change in direction during an observer's movement, things will appear to move. Position constancy is lost. More recent experiments indicate that the same is true if the rate at which things change their direction is altered during the observer's movement, even if the direction of movement itself is not altered.

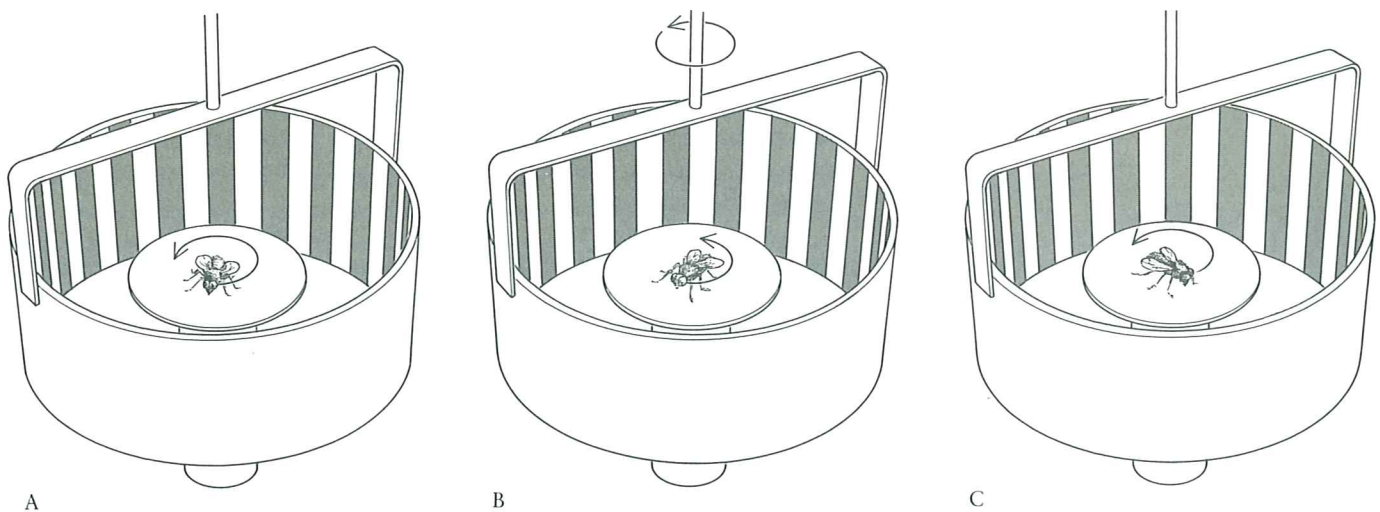
In experiments such as Stratton performed, observers will adapt to this abnormal change in direction during their movement. After a few days, the scene no longer appeared to Stratton to move when he moved. It was



Stratton's inverting lenses yield illusory motion of a scene. When Stratton turned his head from the position shown on the left to the position shown on the right, the retinal images of stationary objects shifted in a direction opposite to their normal direction.

not simply that he grew accustomed to such motion effects and stopped attending to them. The proof is that, on removing the lenses at the end of the experiment, the scene appeared to move whenever Stratton moved and in a direction opposite to the direction in which it appeared to move when he first put the lenses on. This kind of outcome, of perceiving things opposite to the way they appeared when distorting optical devices were worn (generally referred to as a *negative aftereffect*), can be taken as strong proof that an adaptive change has occurred. We can therefore conclude that Stratton's perceptual system learned, while he was wearing inverted lenses, that the change of direction of stationary things during his own movement is toward the direction of his movement, not opposite to it, as is normally the case.

These findings tell us that the specific relations between a change of an object's direction and a change in the observer's position that yield an impression of motion or position constancy can be learned or relearned. They do not necessarily imply that the relations had to be learned in the first place, however. For some animals tested, position constancy is innately determined. In one experiment, the head of a fly was surgically rotated 180 degrees and kept in that position. This had the effect of



reversing the direction of the motion of the image of the stationary scene during the fly's motion, much as did the lenses in Stratton's experiment. What did the fly perceive when it moved? A simple but ingenious experiment, conducted by Horst Mittelstaedt of the Max Planck Institute, that made use of a known reflexlike effect supplied an answer.

When an animal is placed inside a rotating drum lined with vertical stripes (such as the one shown above), it will rotate its eyes, its head, or its entire body in the direction in which the drum is moving. This reflex action is generally referred to as the *optomotor response*; in humans, in whom only the eyes turn, it is referred to as the *optokinetic response*. Before its head was rotated, the fly was placed on the platform inside the drum. When the drum was stationary and the fly happened to move, no optomotor response was evoked. We can thus presume that, despite displacement of the images of the stripes over the fly's retina, no motion was perceived. The fly achieved position constancy. But after the head was rotated and the fly happened to move, it continued turning indefinitely. Apparently, the stripes in the stationary drum appeared to the fly to move when it moved, for the same reason that the scene initially appeared to move for Stratton. Because the stripes appeared to move, the optomotor effect was generated, and the fly turned precisely as it would if the drum had actually been rotating. Such turning produces further apparent rotation of the drum, and so on. Since a normal fly does not engage in the optomotor response when walking or flying, even soon after hatching, we can presume that the world appears stationary during its motion. Thus it is plausible to infer that, for the fly, position constancy is innately determined.

Experiments on position constancy in flies.
 A. When a fly that is rendered incapable of flight spontaneously moves inside a stationary drum, no optomotor response is triggered. B. When the drum rotates around the same fly, the fly circles in order to keep pace with the drum (optomotor response). C. When the fly's head is rotated 180 degrees, and the fly spontaneously moves inside a stationary drum, the fly continues circling indefinitely.

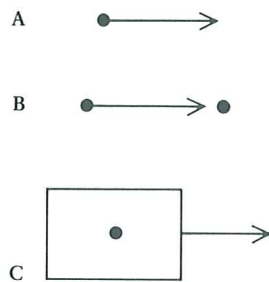
Relative Motion

Ordinarily, a moving object not only changes its direction with respect to us but changes its location with respect to all other stationary things in the scene. This relative change of location can affect the motion we perceive in various ways.

INDUCED MOTION When the moon appears to move across the clouds, the moon is not changing its direction with respect to us—that is, its *egocentric direction*—but the clouds are doing so. If changing egocentric direction were all there were to motion perception, the moon would appear stationary and the clouds would appear to move. The fact that we see the moon as moving suggests that the change in position of an object relative to background objects must be a strong determinant of perceived motion. This effect is called *induced motion*—the inducing of motion in a stationary object by a nearby moving object. One might have predicted that this relative change would simply reinforce an impression that the clouds are moving. The clouds ought to appear to move because they change direction with respect to the observer. The presence of the moon might be expected to further support that appearance by the impression of relative change it yields. Why, then, should the introduction of relative change cause us to see the moon rather than the clouds as moving?

At slow rates of change of egocentric direction—as would often be true of slowly drifting clouds—motion detection is poor. But change of relative location is more readily detected. The following experiment makes this point clearly. In a dark room, a single luminous spot can be set in motion at a speed below our threshold to detect its movement. If a second luminous stationary spot is introduced nearby, however, we immediately do see a spot in motion. Apparently, we are very sensitive to the changing distance between the two spots. Although we will tend to see one of the spots moving, we are equally often wrong as right as to which spot it is. In this experiment, the only usable motion information we are receiving is of a relative kind. Because such information is ambiguous, however, we cannot tell which object's motion is producing the relative change.

In the case of the moon and cloud, then, it is reasonable to suppose that the relative change of position between the two is paramount in our perception but that it is also ambiguous. Therefore, half of the time we should erroneously attribute the change to the moon's motion. However, the moon will almost *always* appear to move when a cloud moves in front of it, not merely half the time. There is a further principle of induced motion that is applicable in this case. An object that surrounds another, or is much larger than it is, tends to be seen as stationary. The

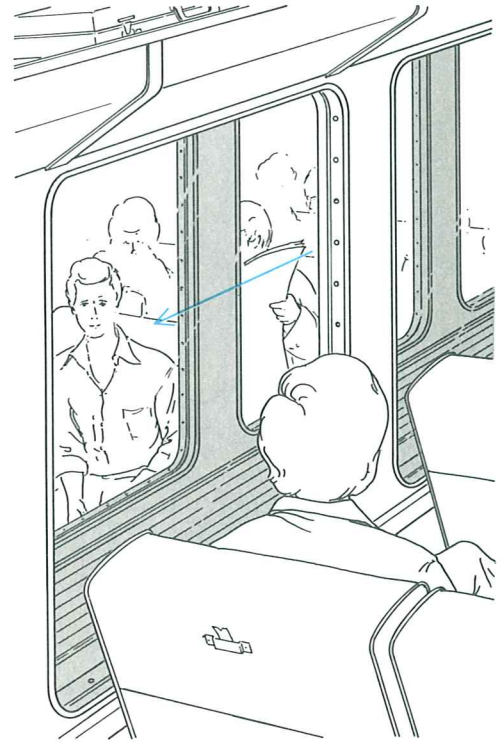


Induced motion of an object. A. An isolated point moving slowly in a homogeneous field may be below the threshold for detecting its motion. B. When a second, stationary point is introduced, the motion is now readily detected, although it may be attributed to either point. C. When the stationary object is surrounded by a moving one, the stationary object will be perceived as moving.

larger object therefore serves as a *frame of reference* with respect to which the relative displacement of other things is gauged. To prove this point, Karl Duncker, a Gestalt psychologist who pioneered investigation of induced movement in the late 1920s, varied the experiment just described by replacing the moving point by a moving luminous rectangle that surrounded the stationary luminous spot. The stationary spot appeared to move on every trial.

Why does this effect occur? Perhaps because the larger or surrounding object serves as a surrogate of the entire visual world. The world as a whole is perceived as stationary, so that anything representing it tends to be interpreted as stationary. This tendency might be thought of as one based upon an "assumption" or preference on the part of the perceptual system.

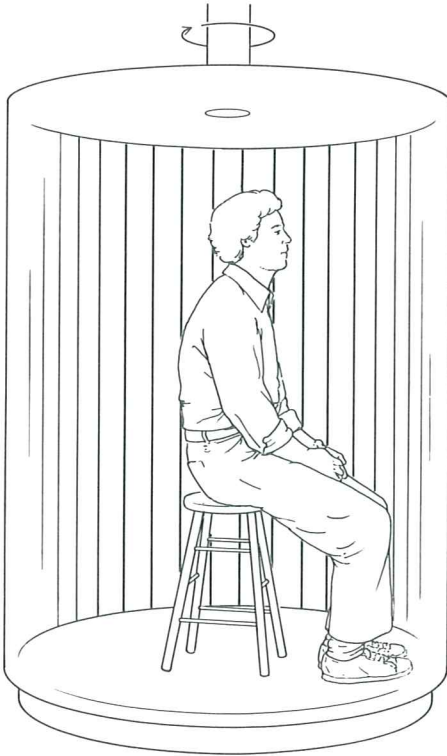
This analysis of the induced motion of the moon can be applied to many other situations. Thus, in daily life, when an object moves in front of a stationary background it seems correct to conclude that its perceived motion is overdetermined—that is, determined by more than one factor. If it is moving fast enough, it will be seen to do so on the basis of its egocentric change, even if nothing else is visible. But, given its change relative to the background, it will be seen to move even if its egocentric change is below the threshold of detection. In typical cases of object motion, then, perceived motion seems to be governed by two independent factors.



Induced motion of the self. Slow displacement of an adjacent train (designated by the arrow) is often experienced as motion in the opposite direction of the train in which we are sitting. The adjacent train then appears to be stationary.

INDUCED SELF-MOTION We ourselves sometimes undergo induced motion. When we are in a stationary train and a train on the adjacent track is in motion, for example, we often misperceive which train is actually moving. A similar effect occurs when we stop for a light in a car. If a car alongside ours begins to roll backward, we often perceive our own car to be rolling forward and step on the brakes. When we look down at the water current from a stationary boat or from a pier, we sometimes experience ourselves as in motion.

Induced motion of the self was demonstrated in the Haunted Swing Illusion, an exhibition at an 1894 fair in San Francisco. Observers sat in a large seat suspended by ropes. The seat seemed to swing back and forth in ever increasing arcs until eventually it turned upside down. No one fell off—for the simple reason that the swing only moved slightly. It was the room that swung back and forth. The people on the swing experienced themselves as in motion and the room as stationary. In this example, the induction effect is powerful enough to overcome information based on gravity, which indicates that the observers are not tilting or inverting and that the room *is* tilting from the upright.



Laboratory arrangement for studying induced self-motion.

Relative change is clearly the determining factor in these cases. Unless we have clear information as to our own motion, such as when we are walking, information about the change in direction of the surrounding scene will be ambiguous. It could be the result of motion of the outer object or objects, or it could be the result of our own motion. If the moving object fills most of our visual field and no stationary objects surrounding the moving one are visible, the visual experience is essentially what it would be if we were moving in a stable environment.

In the laboratory, induced self-motion is studied by seating an observer inside a rotating drum lined with stripes, as shown at left. Ideally, the stationary floor and ceiling are not visible. If we were in the observer's place under these conditions, how could we tell whether it was the drum that was turning or we that were turning while the drum remained stationary? The visual input would be highly ambiguous.

But what about nonvisual information that tells us about our movement and its direction and rate? Nonvisual information ordinarily derives from the vestibular apparatus of the inner ear and is only available when there is change in the speed, or rapid change in the direction, of our movement. Such signals are lacking when we move at a uniform speed. Therefore, if we are inside the drum, we could interpret the absence of nonvisual signals to mean either that we are stationary or that we are turning at a uniform speed. Given this ambiguity, frame of reference again becomes important. The perceptual system assumes that the drum, as surrogate for the environment, is stationary; thus we interpret the changing direction of the drum's stripes as a sign that we are rotating.

There is usually a brief period before this interpretation occurs, however. At first, the drum does seem to turn. Then it appears to slow down and, if we were typical observers, we would begin to experience ourselves as slowly rotating. Finally, the drum appears to stop entirely, and we see and feel ourselves to have as much rotary motion as, in fact, the drum has. The feeling that one is turning is another example of what in Chapter 5 was termed *visual capture*—the tendency of a visual percept to force nonvisual perceptions, such as those gained through touch, proprioception, or audition, to fall into line with itself. It thus seems that induced motion of the self follows the same principles as induced motion of other objects. Relative change and frame of reference are again the determining factors.

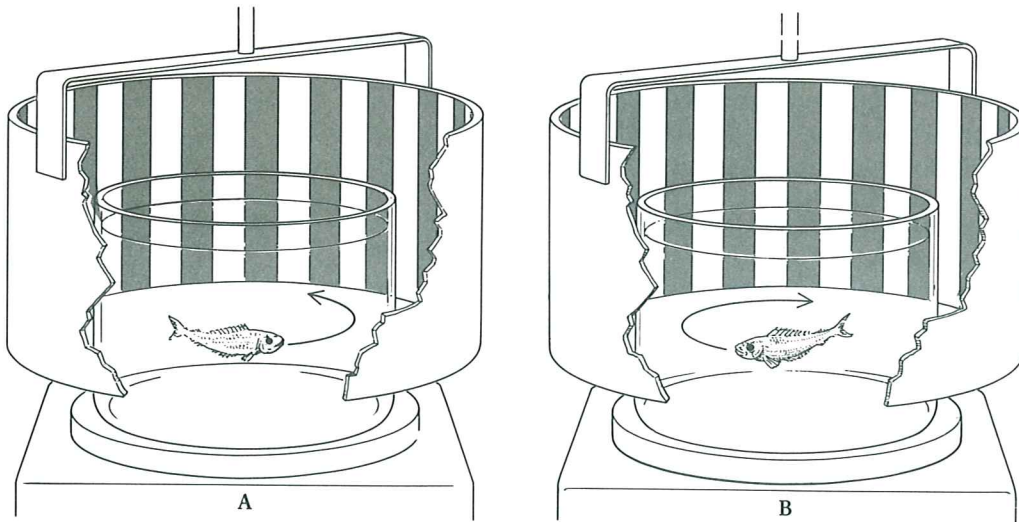
Is there a link between induced self-motion and the optomotor response, since both effects arise when the observer or experimental animal is inside a rotating drum? In the optomotor effect, the animal turns or moves in the direction of the drum's rotation; in the induced-motion effect, observers experience themselves as rotating and do not *do* anything except with their eyes. Unless instructed to fixate a stationary spot

in front of the moving stripes, observers will typically rotate their eyes, pursuing the moving stripes until the stripe pursued goes out of the field, at which point they will snap their eyes back in the opposite direction, the two movements being referred to as the slow and fast phase, respectively, of optokinetic nystagmus. This eye movement is sometimes regarded as the equivalent of what is a more complete motor response in animals.

The prevailing view of the cause of these optomotor or optokinetic responses is that they are reflexlike tendencies to stabilize the retinal image. If such responses were absent, it would be difficult to perceive moving objects clearly. The response is analogous to another reflex: When we turn our heads, the eyes automatically swivel in the opposite direction (even if the eyes are closed). These compensatory eye movements enable us to maintain fixation on an object as we move.

If the optomotor response is simply a reflexlike behavior to guarantee a stable retinal image, there is no connection at all between the optomotor effect in animals and the induced self-motion effect as studied in human subjects. However, another interpretation of the optomotor response is possible. Consider, for example, a fish in a current that tends to carry it downstream. The fish will generally resist the current by swimming upstream, so that it remains in the same place. When the current begins to carry the fish along, the visual situation for the fish is exactly like that of an observer inside a rotating drum. That is, the surrounding visual scene—for the fish, the sides or bottom of the river—is moving. Suppose, as seems reasonable to believe, that induced self-motion causes the fish to experience itself in motion, as being carried away from its position. Because the fish had not intended to swim downstream, the motion it perceives in itself is, so to speak, unwanted, so it swims upstream to maintain its position.

Deborah Smith and I performed some experiments with tropical fish to test this hypothesis. We placed a fish in a cylindrical glass tank that was surrounded by a drum lined with vertical stripes. The top was covered except for a small hole in the center through which the fish could be viewed. In one experiment, we rotated the tank about its center, thus generating a current because of friction, while keeping the surrounding drum stationary, as shown in the left-hand illustration on the following page. This essentially simulates the situation of the fish in the river carried downstream by a current. We reasoned that the fish does not directly react to the water current but ordinarily responds to it only by its visual consequences—that is, being carried away from visible objects in its field. To prove this, we first wrapped the tank with white paper so that the fish could not see through the tank. Under these conditions, the fish made no effort to swim against the current going around the tank. When we removed the paper so that the fish could see the stationary stripes,

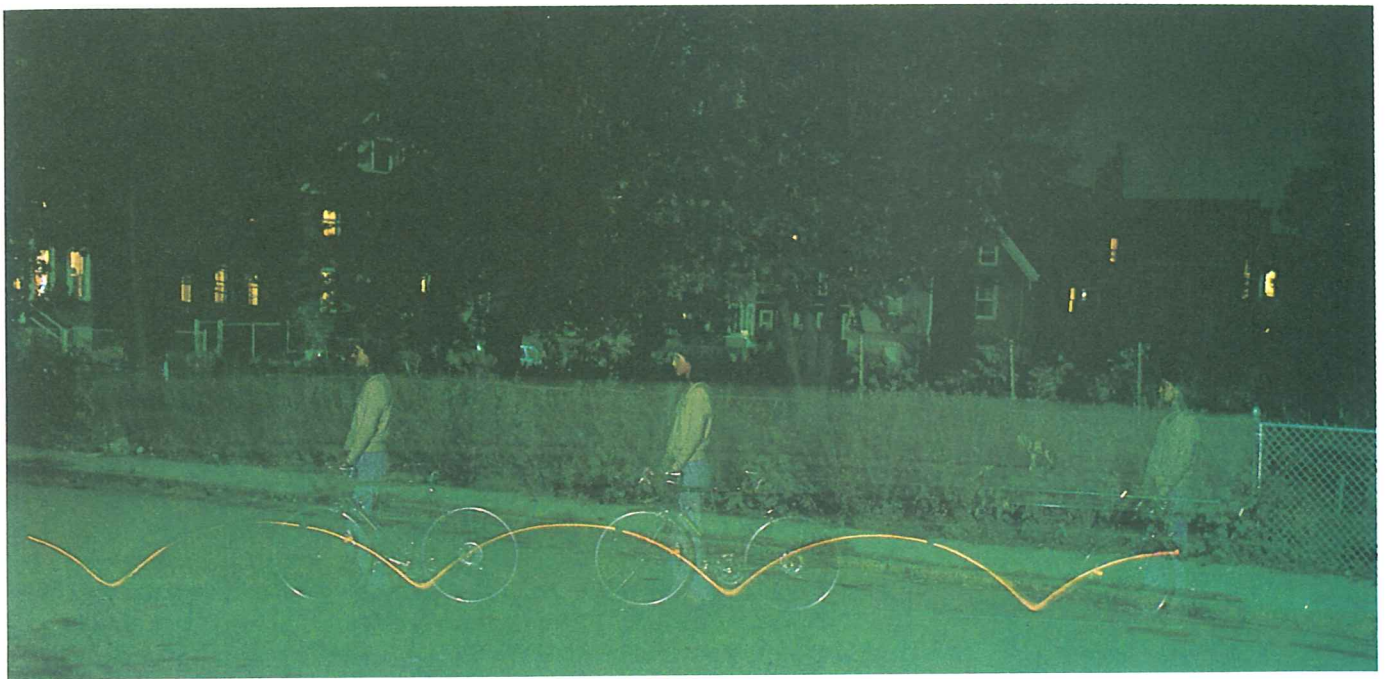


Experiments on the optomotor response in tropical fish. A. When the tank is rotated and the outer, striped drum is visible but stationary, fish swim against the current. B. When the tank is stationary and the striped drum is rotated, fish swim to keep up with the drum's moving stripes.

however, all fish swam vigorously against the current, thus remaining in place opposite any given set of stripes.

In a companion experiment, we kept the tank stationary while rotating the drum, as shown in B, above. Now the fish swam vigorously in the direction of the drum's motion, keeping pace with it, even though there was no current. This condition would be regarded as the optomotor paradigm, whereas the one with the rotating tank and stationary drum would not. But they are psychologically and behaviorally identical. They both illustrate that a surrounding visible structure, when moving, generates or induces an experience of self-motion, while the structure itself appears to be stationary. In an animal such as a fish, *that* experience in turn generates a tendency to compensate for such unwanted movement of the self; the animal attempts to maintain its position in its perceived world. In a human observer, the self-motion seems to be tolerated; it elicits no behavior designed to nullify it, at least in an experimental situation. (In a more natural situation, such as in a river, a person might well react as the fish does, by swimming upstream in order not to be carried away downstream.) The optokinetic response is undoubtedly motivated by the tendency to stabilize the moving image, but, according to the present hypothesis, it has nothing to do with induced self-motion. It occurs both when the drum appears to be rotating and the self is stationary and when the drum appears to be stationary and the self is experienced as moving.

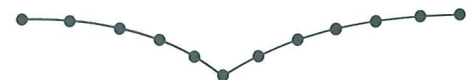
If this interpretation of the optomotor response in fish is correct, induced self-motion may be far more prevalent in the life of animals than we realize. It is perhaps confusing to think of situations in which the observer is in motion as exemplifying induced motion—as in the case of



the transported fish—but the fact is that the perceptual situation is identical here to the one usually defined as yielding induced self-motion, where the surroundings are moving and the observer is stationary. If this is true, then there are many other cases in the daily life of human observers in which induced self-motion is occurring. Whenever we are transported in a vehicle and moving at uniform speed, it is only by induced motion that we see ourselves in our vehicle as moving. With our eyes closed, the only cue to motion would be vibrations, and that is insufficient. Even with our eyes open and, let us say, only a single light visible, we would tend to misperceive *it* as moving if we did not know that we were in a moving vehicle. But with the full scene surrounding the vehicle visible, we do perceive ourselves to be in motion. Therefore, the determinant here is the same as if our vehicle were stationary and the scene contrived to move past us. The underlying factor of great theoretical importance in this entire discussion is the tendency for the surround to be “assumed” to be stationary, to be interpreted as the frame of reference, and thus to yield the various consequences for perceived motion that we have considered. In the next section, we will see certain other consequences of relative motion and the frame of reference.

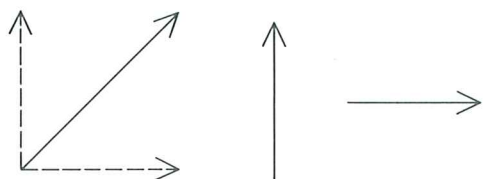
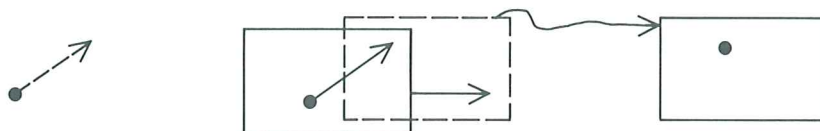
Illusions of Direction

A reflector on the wheel of a moving bicycle seen on a dark night will appear to move in a peculiar way. When the wheel rolls, the spot of light appears to move along a path that mathematicians call a cycloid curve, as shown in the photograph and the illustration above.



A spot on the rim of a rolling wheel traverses a cycloidal path through space. In the time-exposure photograph, a reflector shows the path traversed by a point on a bicycle's wheel.

(Left) A spot moving along an oblique path in a homogeneous field is perceived veridically. (Right) When a horizontally moving frame surrounding the spot moves along with it, the spot appears to be moving vertically.



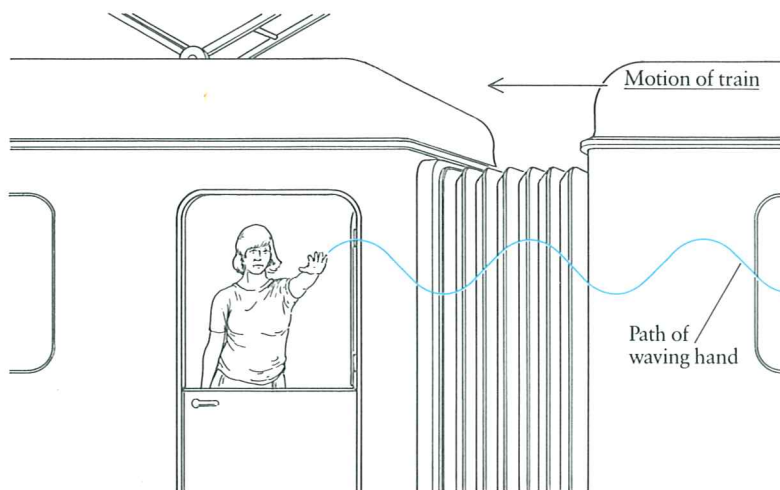
The two components of perceived motion of an object traveling along an oblique path.

The reflector travels this path because it is both revolving around the axis of the wheel *and* being carried forward as part of the wheel. If the eyes are held still, the reflector's image also moves over the retina along a cycloidal path. Therefore, what we perceive in looking at the moving bicycle's reflector at night can be said to be correct and not an illusion. But when we watch the moving bicycle's reflector in daylight—or, for that matter, any wheel rolling—we no longer experience the cycloidal path of motion: All points on the wheel appear to revolve around its axis and the wheel-as-a-whole appears to be rolling along a straight path.

Before trying to understand these perceptions, consider the following example illustrated at the top of the page. If we view a spot of light traveling along an oblique path in an otherwise dark room, we will perceive its motion correctly. If we view the spot traveling the same path, but this time surrounded by a rectangular frame that is moving horizontally along with the spot such that both will reach their rightmost and leftmost positions at the same moment, the spot will no longer appear to move obliquely. Our dominant impression will be that it is moving up and down. However, we will also have the impression, although a less strong one, that the spot belongs to the rectangle and is moving horizontally along with it.

Thus, as has been suggested by Duncker and by the psychologist Gunnar Johansson at the University of Uppsala, under some conditions a path of motion will yield two components of perceived motion, as if the actual path were split into two vectors, as shown in the illustration at left. Some insight into the basis of this kind of effect can be gained by considering an example from daily life. Suppose you watch a friend leaving on a train. Your friend waves at you. You perceive the waving hand moving up and down, although, in fact, as the train moves forward, the hand is moving along a path similar to the one shown on the facing page, above. In this example, perceiving the hand as moving vertically is not an illusion because, relative to the train, it *is* moving vertically.

There are conflicting frames of reference in both examples. Relative to the observer, both the spot in the laboratory example and the hand of the person waving are moving obliquely. But relative to the moving frame of reference—the rectangle or the train—these objects are moving up and down. This latter relation seems to dominate our perception. However, there is a second component to our perception of the movements: We see

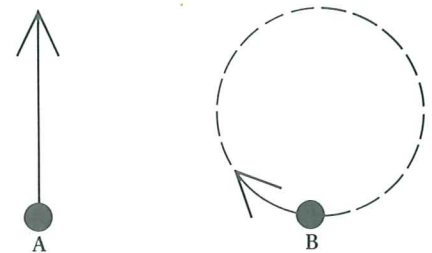


The path of the person's hand waving goodbye as the train leaves a station resembles that of a sine curve, but it is perceived to be moving up and down.

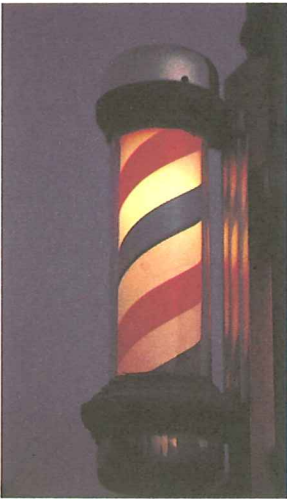
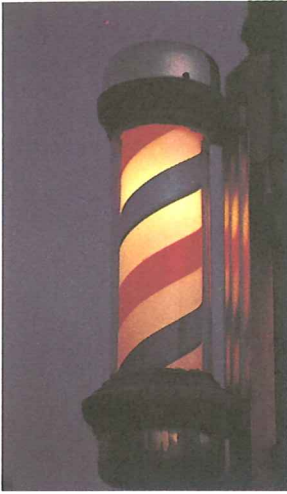
the spot and the hand as partaking of the horizontal motion of the objects that encompass them (frame or train), apparently because we perceive the spot as *belonging* to the frame and the hand as *belonging* to the train. The two components of perceived motion, vertical and horizontal, together fully account for the changing angular direction of the spot or hand with respect to the observer.

Johansson has shown that this kind of perception can occur even when no visible structure serves as a frame of reference. In the illustration at right, one spot, A, moves up and down. Another spot, B, moves along the path of a circle. However, B's motion is linked to A's vertical motion so that B arrives at the top and bottom of its circular path when A arrives at the top and bottom of its path. If A is not visible, B appears veridically to move around a circular path. But when A is visible, B is not perceived to move in a circle. Rather, it appears to move back and forth horizontally, approaching and receding from A. In addition, both A and B appear to move up and down together.

There is some disagreement over how to explain this effect. One explanation is that B's motion is purely horizontal relative to A's, and that such relative change is salient in our perceptual experience. Therefore, we perceive this change. But, in addition, both spots are going up and down together, and we perceive this fact secondarily. An alternative explanation evokes the principle of grouping by "common fate," discussed in Chapter 5: When objects move together in the same direction and at the same speed, we tend to perceive them as belonging together. The spots in our example are moving together in the vertical direction. Once we see both spots as a group, this structure becomes a frame of reference with respect to which the horizontal component of B's motion is noted. In both explanations, however, the net result is that the circular motion of B is divided into two vectors of perceptual motion.



Spot B, moving in a circular path, is perceived veridically when spot A is not visible. When spot A is visible, spot B appears to move back and forth horizontally while both spots as a group appear to move vertically.



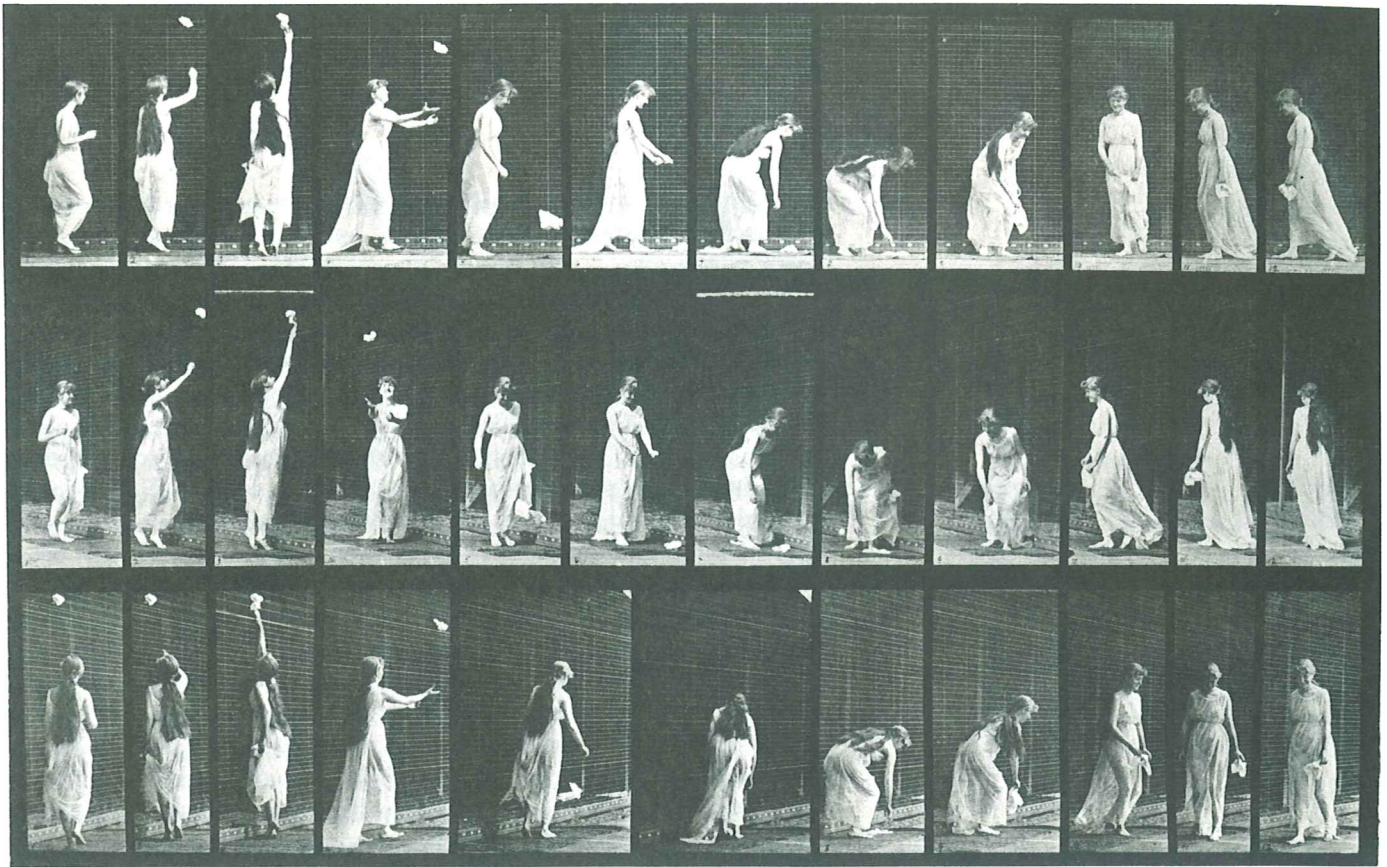
Successive views of a barber pole. The stripes on a barber pole appear to move vertically although every point in the helical pattern is rotating in a horizontal plane around a vertical axis.

Now we can reconsider the spot on the rim of the rolling wheel. The spot's true path through space is not perceived unless the rest of the wheel is invisible, as in the case of the bicycle seen in the dark. When just a few additional spots on the wheel are visible, the wheel becomes a frame of reference for the spot. The spot is now seen as revolving around its axis. Because it "belongs" to the wheel, it also is seen as partaking of the wheel's horizontal, linear motion. Therefore, there are two components of motion that are perceived.

These examples of directional illusion and those of induced motion suggest the following conclusions: The motion of one object relative to other objects is particularly important in the perception of movement. Under certain conditions, one object in the field will serve as frame of reference with respect to which other objects will be seen to move. The frame of reference is often "assumed" to be stationary so that any motion relative to it is attributed to other objects. When the frame of reference is seen to be in motion, objects seen with respect to it will appear to have different components of movement, one based directly on relative change and another based on their belonging to the frame and partaking of its motion. Finally, under the right conditions, observers may perceive themselves to be in motion when a nearby structure that is in motion is assumed to be stationary.

An illusion of direction of motion that is very different from the kinds thus far discussed is the barber-pole illusion, illustrated at the left. One tends to see stripes moving down (or up), although in fact any region on the colored helical stripe that curves around the barber pole is simply rotating around the pole and not displacing downward or upward. In order to see this motion veridically, however, we would have to distinguish some specific point on the helix. Then we would detect its rotation in a horizontal plane. Without such a distinct point, however, we have no good information as to how the contour of the helix is moving. The stimulus is thoroughly ambiguous, as is shown by the successive views of the pole in the illustration. Under the circumstances, we tend to "assume" that the visible parts of the contour at time 1 are the same as those at time 2—that is, that these regions have the same physical identity. In fact, they are different because the helix is rotating. Thus those visible at time 1 will be occluded by time 2. If the parts were the same, the stripe would have to be moving directly downward, and that is precisely what we perceive.

Another way of stating the barber-pole effect is that we have a tendency *not* to perceive the points constituting a visible contour as moving out of view, or as changing location and being exchanged for new points, when there is no good stimulus information that they are doing so. Under some conditions, this tendency can lead to perceiving moving lines as

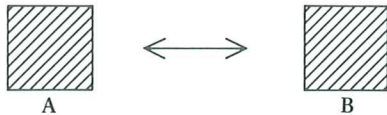


stationary. This tendency, in turn, leads to various other illusions, such as the impression that the circles in the stereokinetic display shown on page 69 are not rotating when the display is turning. If they are not rotating, they must be changing their positions by sliding around. In my opinion, the difficulty the perceptual system has in explaining this perception leads it to search for a better solution. The depth solution discussed in Chapter 3, in which the object is perceived to undergo perspective change, is precisely that. The same tendency not to perceive rotation of rotating circular or curved patterns leads to the perception of a rotating spiral as expanding or contracting, since each region of it then appears to be moving only inward or outward, depending upon the direction of the spiral's rotation.

Apparent Movement

Most people realize that moving pictures, including television, are illusions based on a succession of still pictures projected on a screen. But many believe that the illusion results from the eye's tendency to continue to transmit signals to the brain from a frame of film even when it is no

The illusion of motion. Eadweard Muybridge took these sequential shots of a woman throwing a handkerchief into the air and picking it up, each row showing the same scene from a different perspective. When the shots in each row are viewed successively at a rapid rate, they lead to the impression of movement. The apparent-motion effect is the basis of perceiving movement in television and moving pictures.



Arrangement for studying apparent motion. Objects A and B are alternately flashed, creating the impression of a single object moving back and forth.

longer projected on the screen, thus filling the gap between frames. However, such persistence of vision explains only the absence of flicker, not apparent motion.

Students of perception have not done much better in their attempts to explain this illusion of motion. In the laboratory, *apparent motion* (also referred to as *stroboscopic motion* or the *phi phenomenon*) is studied in its utmost simplicity by flashing a single object or line in one place, and then, a short time later, flashing a similar object or line in another place. If the spacing and timing are just right, the observer will see the object or line moving from the first location to the second (from A to B in the illustration at left). Usually, the cycle is repeated and the observer sees the object moving back and forth. Why do we tend to see movement when the stimulus consists of one stationary object followed by another? The presumption is that, if we can unravel this problem, it will provide a key for understanding motion perception in general.

One approach to the problem is to consider apparent motion as a special case of real motion and to explain the perception as the result of motion-detector neurons firing in the visual nervous system. If the successive stimulation of adjacent retinal cells leads to the rapid firing of neurons that are specialized to detect such stimulus motion, then the successive stimulation of retinal cells that are farther apart may cause the rapid firing of neurons that detect the stroboscopic stimulus sequence.

Horace Barlow and William Levick at the universities of California and Cambridge have shown that precisely such a successive stimulation of neighboring, but not directly adjacent, regions of a rabbit's retina will trigger the response of neurons in its visual nervous system.

We might regard this approach as a sensory theory of apparent movement. While a theory of this kind may provide the explanation of perceived movement under stroboscopic conditions in animal species lower on the phylogenetic scale (fish, for example), it is inadequate to explain how we perceive it. First, apparent movement can be seen across a considerable angular distance, far enough for it to be unlikely that the two stimulated regions of the retina would be associated with the same motion-detector neuron in the brain. We can see such motion when a stimulus, A, falls on one side of the retina and a second stimulus, B, on the other. In fact, this probably occurs often, such as when the eyes are fixating between A and B. Under such conditions, A is projected to one hemisphere of the brain and B to the other. As can be seen in the illustration on page 7, the only connection is through neurons that cross in the structure of the brain known as the corpus callosum.

Implicit in the sensory theory of apparent motion is the assumption that what distinguishes apparent from real motion is the extent of separation between A and B on the retina. But that assumption may be incor-

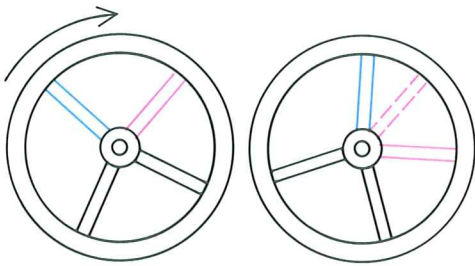
rect. *A* and *B* are separate from one another in perceived space, whereas an object in real motion is seen to be located in a series of adjacent positions in space. If we track a really moving object, we perceive it to be moving even though its image remains stationary on the retina. Perhaps, then, an analogous situation prevails in the case of apparent motion. In an experiment Sheldon Ebenholtz and I performed some years ago, observers had to synchronize their eye movements with the flashing on and off first of *A* and then of *B*. As *A* appeared, observers looked directly at it. Thus the image of *A* fell in the central region of the retina, the fovea. As *A* disappeared, observers rapidly shifted their eyes to point *B*; just as the eyes reached that position, *B* flashed. It, too, then projected onto the fovea. The observers perceived apparent motion from *A* to *B*. In this case, a simple sensory explanation will not suffice because only one region of the retina was stimulated, not two. A single retinal region can represent two locations in perceived space because the direction of stimulation is interpreted differently on the basis of the two different positions of the eyes. In that respect, this experiment is analogous to the one in which we track a really moving object.

This outcome suggests an inference theory of apparent movement. According to this theory, apparent movement is a solution to the problem posed when object *A* disappears in one place in the scene and another object, *B*, suddenly appears in another place. After all, this sequence is quite similar to real motion, particularly when it is rapid. If one views a rapidly wagging finger, the conditions are much like those of apparent motion, except that the finger remains visible throughout its path. But Lloyd Kaufman and his associates at New York University have demonstrated that the visibility of the path *between* locations *A* and *B* during such rapid motion is essentially a blurred streak and of little use for motion perception. They showed that, if the end positions of *A* and *B* (where, in the present example, the finger is momentarily stationary) are occluded so that only the intervening blurred motion is seen, observers do not perceive apparent motion. Conversely, if the end positions of the wagging finger are visible but its intervening path is not, motion *is* perceived. In this case, we have converted real to apparent motion.

Therefore, real motion and apparent motion are very similar if not identical, at least at fast speeds. This fact solves one puzzle about apparent motion: why we perceive apparent motion when there are few if any circumstances that animals or human beings encounter in the natural environment in which the conditions of apparent movement prevail. If the perception of apparent motion serves no adaptive purpose, why did we evolve in such a way that we could perceive it? The work of Kaufman and his associates suggests an answer: Perception of rapidly moving objects was necessary for survival, and the conditions for such perception



Apparent motion of multiple objects. The three spots in A, designated here by the white spots, alternate with the three spots in B, designated here by the dark spots. (In an actual experiment, all of the spots would be the same color.)



The wagon-wheel effect. In moving pictures, a wheel is often perceived to roll backward when in fact it is rolling forward.

reduce to those for apparent motion. Thus, in an apparent-movement display, when the conditions mimic those of real, rapid motion, entailing sudden disappearance of an object in one place and its reappearance in another, our perceptual system makes the plausible inference that the object has moved.

For apparent movement to be seen, the temporal interval between *A* and *B* must be neither too long nor too short. Although this fact has been known since apparent motion was first discovered, the reasons behind it have never been clear. The inference approach, however, may help to explain it. If the temporal interval is too brief, we tend to perceive both *A* and *B* simultaneously. This fact is based on persistence of vision. If *A* is still visible when *B* appears, the perceptual system can hardly infer that *A* has moved to *B*! If the interval is too long, *A* must be inferred to be moving rather slowly across the intervening space. After all, the object must be assumed to be moving at a speed such that it reaches *B* just as *B* appears. If an object were to be moving slowly, it ought to be visible between *A* and *B*. Only at fast speeds does the perceptual system “expect” the object to be little more than a blur between *A* and *B*. Therefore, if the speed is inferred to be slow and the object is invisible, the inference that the object is really moving is rejected.

So far, we have considered the case of a wagging finger or other single stimulus object. But in moving pictures several things are often moving or different parts of one object are moving simultaneously. For example, when we see a woman walking across the screen, we usually see feet, arms, and the entire body move. Consider the simplified situation in the upper illustration at left, in which the three white spots represent *A* (flashed first) and the three dark spots represent *B* (flashed second). What spot in *A* should we expect will be seen to be moving to what spot in *B*, and why? This issue is referred to as the correspondence problem.

The prediction that a sensory theory of apparent movement should make is one based on proximity. It should be predicted that whatever spot in *B* is nearest to a spot in *A* will be the one to correspond to it such that motion will be seen between them. Proximity is a powerful principle for predicting correspondence in apparent motion displays, and it is a powerful principle of perceptual grouping. We can make use of it to explain a common but curious phenomenon of apparent motion. In movies, the wheels of a vehicle often seem to roll backward as the vehicle moves forward. This effect, which has been called the wagon-wheel effect because it is frequently seen in wagons used in Western movies, can be explained as follows. Consider one spoke of a wheel, that shown in magenta in the illustration in the left margin. In the first frame of the film, the camera records the wheel in the position on the left in the figure; in the second frame, the camera records it in the position on the right in the figure, the wheel having turned about 50 degrees. We will tend to see the

spoke shown in magenta as rotating counterclockwise, the principle of proximity suggests, because, in the second frame, the spoke shown in blue lies closer to the magenta spoke's position in the first frame than does the actual new position of the magenta spoke. Thus, we tend to identify the spoke shown in blue in the second frame as that shown in magenta in the first frame. But all the other visible points in the wheel are recorded in each frame in the same locations relative to one another; thus, the wheel as a whole appears to turn backward.

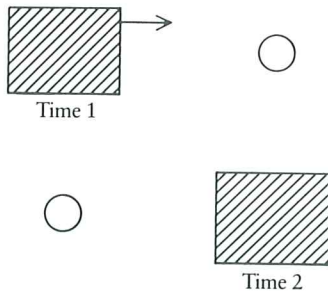
If proximity were to govern correspondence in all cases, however, we would have to predict that, in the upper illustration on the facing page, the second spot in *A* would appear to move to the position of the first spot in *B*, and the third spot in *A* would appear to move to the position of the second spot in *B*, while the first spot in *A* and the third spot in *B* would not correspond with anything. A sensory theory, or any theory based *only* on stimulus proximity, is "blind" to the content of each stimulus unit and its role in the whole configuration. But an inference theory suggests a very different conclusion. If *A* and *B* each consists of three spots, the most plausible inference is that *A* has moved as a whole to *B*. Thus, we would predict that the first, second, and third spots in *A* would appear to move to the respective positions of the first, second, and third spots in *B*. In general, we perceive this kind of sequence in just this way.

An even more striking correspondence occurs when some of the spots in *A* and *B* actually overlap, as shown in the illustration to the right. In the illustration, *A* consists of spots 1, 2, and 3, while *B* consists of spots 2, 3, and 4. This kind of experiment was done 60 years ago in Berlin by Josef Ternus, a student of Max Wertheimer. Here, we have the option of perceiving some spots as simply "flashing" on and off in place. Under some conditions, however, we see the entire configuration as moving back and forth. Thus, for example, the middle spot in *A* corresponds not with the leftmost spot in *B*, to which it is physically identical, but with the middle spot in *B*, with which it perceptually corresponds, since it is the middle spot in both *A* and *B*. Ternus referred to this as *phenomenal identity*. What governs correspondence is the perceptual (phenomenal) identity or role of a part in a whole, not simply the physical identity or physical proximity of the part in *A* and *B*.

Certain findings that at first seem to challenge the inference theory can in fact be reconciled with it. For example, Paul Kolars and James Pomerantz, then at the Bell Telephone Laboratories, demonstrated that apparent movement is easily seen when the two separate images are different shapes. If *A* is a circle and *B* a triangle, observers will perceive the circle changing shape as it moves, becoming a triangle by the time it reaches *B*. This effect suggests that the sudden disappearance of the object at *A* and the sudden appearance of an object at *B* creates such a strong presumption of movement from *A* to *B* that the movement is



In this apparent-motion display, spots 1, 2, and 3, shown as white, compose A and are shown first, while spots 2, 3, and 4, shown as black, composing B, are shown next. The middle and rightmost spots in A overlap with the leftmost and middle spots in B. Yet the cluster of three spots in A is often perceived to move as a group to the cluster of three spots in B. It has recently been demonstrated that if the time interval between exposures is very short, the successive stimulation of spots 2 and 3 will produce the impression of stationary rather than moving objects. To the observer, these spots appear to be "on" continuously (because of persistence of vision), and thus no inference is made that they moved.



The rectangle alternately covers and uncovers the two spots, which are present throughout the experiment. When the rectangle is not visible, the spots appear to move back and forth. When it is visible, the spots are not perceived as moving.

perceived despite the dissimilar shapes. The perceptual system thus seems to account for the dissimilarity in an ingenious way, by perceiving that the object deforms as it moves.

One final experiment in support of the inference view is worth mentioning. Based upon an earlier finding by Arnold Stoper, then at Brandeis University, Eric Sigman and I performed the experiment illustrated at left. Two spots appeared and disappeared at spacings and intervals that normally would yield an impression of apparent movement. However, this appearance and disappearance was achieved by moving an opaque rectangle back and forth over the spots. When the rectangle itself was not visible, observers perceived the spots moving back and forth, as would be expected. When the rectangle was visible, however, they did not perceive the spots to be moving. Instead, they perceived them to be permanently present but alternately covered and uncovered by the rectangle. Although images of the spots stimulated the retina at the appropriate spacing and timing, the sequence did not yield the illusion of apparent movement. This finding suggests that we ordinarily perceive apparent movement not because it is an inevitable sensory outcome of stimulation but because it is the best explanation of the otherwise inexplicable sudden appearance and disappearance of objects. But in the present experiment another solution is available, namely permanently present spots undergoing covering and uncovering.

The sensory theory and the inference theory may both be correct. Oliver Braddick of Cambridge University has argued that there are two different kinds of apparent motion. One is based on very small separations between the images of *A* and *B* on the retina and very short time intervals between them. It is likely that the mechanism observed by Barlow and Levick is responsible for apparent motion perception under such conditions. Braddick calls this the short-range process. The other kind of apparent motion, the long-range process, is based on greater spatial and temporal separations between *A* and *B*. It is unlikely that the sensory motion-detector mechanism can be responsible for apparent motion under these conditions. If Braddick's controversial classification is correct, it is plausible that the inference theory applies here and that the findings cited in support of such a theory derive from conditions that favor the long-range process.

The Autokinetic Effect

A striking illusion of motion occurs when a single star seen against an otherwise homogeneous sky appears to drift across the field of vision. This illusion can be recreated in the laboratory by asking observers seated in an otherwise dark room to view a single spot of light. Soon the spot appears to drift slowly in a particular direction. This *autokinetic*

effect, as it is called, is highly susceptible to suggestion, the studies of social psychologists show. When “planted” subjects report motion of the spot in a certain direction, or of a particular magnitude, a naive subject will often report perceiving the spot to move in just that way.

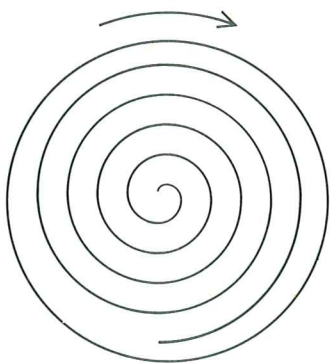
What causes the autokinetic effect? Investigators do not know for sure, but certain facts about motion perception already discussed here shed some light on it. We have seen the importance for motion perception of an object's change in location relative to other objects or to a frame of reference. Conversely, the absence of an object's change in location relative to a background must be important information in perceiving an object as stationary. In other words, a stationary spot seen within a stationary rectangle will not appear to move, no matter how long we look at it. But without the rectangle, the spot's location in a homogeneous background (such as a dark room) is not sufficiently anchored to a frame of reference.

Under these conditions, the only basis for perceiving the spot's location is our knowledge of where the eyes are looking. If the eyes were to be slowly drifting when viewing a spot, we could be tracking a spot that was moving slowly. Perhaps that explains why suggestion can be effective. On hearing that the spot is moving, say to the right, we can imagine that we are tracking it to the right when, in fact, the eyes remain stationary.

Some investigators have argued that the autokinetic effect results from actual eye movements. The idea behind this argument is simply that, with eye movement, the image of the spot displaces over the retina and that retinal displacement causes the illusion. Such a theory is inadequate because, as we have seen, stationary objects do not appear to move every time the eyes move. Position constancy is achieved, presumably because retinal displacement is discounted when the perceptual system “knows” that it is caused by eye movement. For an eye-movement theory of the autokinetic effect to be tenable, it would have to be maintained that the eyes move but that the brain does not “know” that they are moving. One difficulty for this theory is that it must also predict that an entire stationary scene will appear to move, not just an isolated spot. I suggest that it is not eye movement that causes the illusion but the illusory misperception of eye behavior. The eyes are stationary but are misperceived to be tracking the (stationary) spot because the perceptual system “believes” for some reason—whether it be suggestion or self-suggestion—that the spot is drifting slowly across the field.

The Aftereffect of Movement

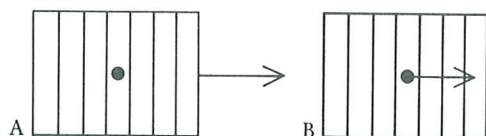
After viewing a continuously moving display such as a waterfall, stationary contours appear to move in the opposite direction for a brief interval.



A spiral used in demonstrating the aftereffect of motion.

In the laboratory, a rotating spiral is often used to generate this *aftereffect of movement*, which is sometimes called the *spiral*, or *waterfall*, *illusion*. If the moving spiral shown at left is viewed for 30 seconds or more while the eyes are fixating its center, and if the spiral is then stopped, it will still appear to be moving, but in the opposite direction. The effect is strongest immediately after the spiral stops, and then it gradually disappears. When the spiral is rotating, it will appear to be either expanding or contracting, depending upon the direction of its rotation. When it stops, it will appear to be either contracting or expanding. In other words, the aftereffect is always opposite in direction to the initial direction of motion. By the same token, if another stationary object, even a person's face, is viewed thereafter instead of the spiral, it will appear to be expanding or contracting for a short duration.

What causes this aftereffect? The evidence strongly suggests the theory that it results from sensory adaptation to contours moving over the retina, in a specific location on the retina. Stuart Anstis and Richard Gregory, then at Cambridge University, performed some simple experiments that demonstrate this. In one experiment, illustrated in A, left below, observers either tracked moving stripes or looked at a stationary spot while the stripes passed in front of them. Although the stripes appeared to move in both cases, only in the second, in which the images of the stripes displaced across the retina, was an aftereffect produced. In another experiment, illustrated in B, left below, observers tracked a dot moving across stationary stripes. Although here nothing was seen to be moving, the images of the stripes moved over the retina, creating an aftereffect. Therefore, the effect is misnamed. It should be called the aftereffect of retinal displacement, not the aftereffect of movement.



Arrangement for the experiment on the aftereffect of motion. A. When observers fixated the stationary point, they experienced an aftereffect of motion, whereas when they tracked the moving stripes, they did not. B. When observers tracked a moving spot over the stationary stripes, an aftereffect was created.

Why should contour displacement over the retina lead to a motion aftereffect? To answer this, it will be helpful to consider a color aftereffect. If one fixates a point while viewing a colored region, and then views a gray region in the same location, the gray region will appear tinged with the complementary color. This effect is referred to as successive color contrast. The effect is localized within the region on the retina exposed to the particular color (just as the motion aftereffect is localized within the region of the retina exposed to the motion of contours). The explanation is that cells in the visual system most sensitive to, let us say, blue are satiated. For this and other reasons, the normal balance between yellow and blue in this region is upset. In subsequently viewing an achromatic gray region, the cells that signal the sensation "yellow" are more active than those that signal "blue," so that the gray region appears somewhat yellowish.

By the same token, some cells in the visual system are most responsive to one direction of contour motion. If these are fatigued, the cells respon-

sive to the opposite direction of contour motion are, by comparison, more active. Hence stationary contours stimulating that region of the retina will create an impression of motion in the opposite direction. These adaptation effects, of both color and motion, are clearly sensory in origin. In fact, the motion aftereffect is paradoxical in one respect. A sensation of motion (or of expansion or contraction) does exist, but the contours do not appear to be going anywhere. No doubt this occurs because other information continues to indicate no change in location.

If this kind of explanation of the aftereffect of motion is correct, the phenomenon is different from all the other kinds of motion perception that were considered in this chapter. Whereas it can be explained in terms of localized sensory mechanisms and is not an aftereffect of *motion perception* but rather of a certain kind of sensory stimulation, the other phenomena cannot be explained simply in terms of sensory mechanisms and *do* concern the perception of motion. Contrary to what might seem to be a plausible explanation of motion perception, the displacement of an object's image over the retina cannot account for such perception, although it is relevant information to be taken into account. We have seen that illusions of motion of various kinds—induced, directional, apparent, and autokinetic—as well as the perception of real motion, are based on more complex central processes entailing constancy operations, relativistic comparisons often based on structures serving as reference frames, and unconscious problem solving.

A number of new concepts and principles have thus emerged in connection with the various phenomena of perceived motion that were not relevant in the earlier discussions of static phenomena. In particular, we have seen for the first time how the body of the observer, the visible self, is another object in the field that conforms to the same lawful processes that govern the perception of other objects. Some of these same concepts will come up again in the next chapter, where we consider how we perceive the orientation of objects and ourselves in the world.