

CHAPTER 4

Motion Perception

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INTRODUCTION AND OVERVIEW

Gordon Lynn Walls, a comparative anatomist, observed, “If asked what aspect of vision means the most to them, a watchmaker may answer ‘acuity,’ a night flier ‘sensitivity,’ and an artist ‘color.’ But to the animals which invented the vertebrate eye, and hold the patents on most of the features of the human model, the visual registration of *movement* was of the greatest importance” (Walls, 1942) p. 342.

The rich and rapidly expanding scientific literature on visual motion perception suggests that Walls was right: To organisms all up and down the phylogenetic scale, visual motion perception is of unmatched importance. Visual motion serves a wide variety of crucial roles: wayfinding (optic flow), perception of shape from motion, depth segregation, judgments of coincidence (time to collision, time to filling a tea cup), judgments of motion direction and speed, and perception of animate, biological activity. Sometimes, the presence of motion can compensate for deficiencies in other forms of visual information, as Figure 4.1 shows. The three images in the figure are frames from a video showing a person performing a common action. Clearly, no single frame conveys sufficient spatial structure to permit recognition that a person is present, let alone recognition of what the person might be doing. However, the complex patterns of

visual motion generated when these frames are displayed as part of a video convey immediately that a person is present and that the person is in the process of sitting down (Bobick & Davis, 2001).¹

Recent decades have produced major advances in understanding of visual motion perception.² Many such advances have come from complementary approaches to analyzing motion: psychophysical, computational, and neurophysiological. It is now known that the detection and analysis of motion are achieved by a cascade of neural operations, starting with the registration of local motion signals within restricted regions of the visual field and continuing with the integration of those local motion signals into more global descriptions of the direction and speed of object motion. Physiological studies of animals—most notably cats and monkeys—have revealed some of the neural hardware comprising this hierarchical processing scheme. Recently, exciting

¹To download the video from the Internet, go to <http://www.cis.ohio-state.edu/~jwdavis/Archive/blurmotion.mpg> OR <http://www.cis.ohio-state.edu/~jwdavis/Archive/blurmotion.mov>.

²Previous editions of this handbook paid scant notice to the topic of our chapter. In the first edition, Graham (1951) spent just six pages on motion perception, emphasizing research on apparent motion. In the second edition, more than three decades later, the coverage was increased by only ten pages distributed over two chapters (Hochberg, 1988; Westheimer, 1988).

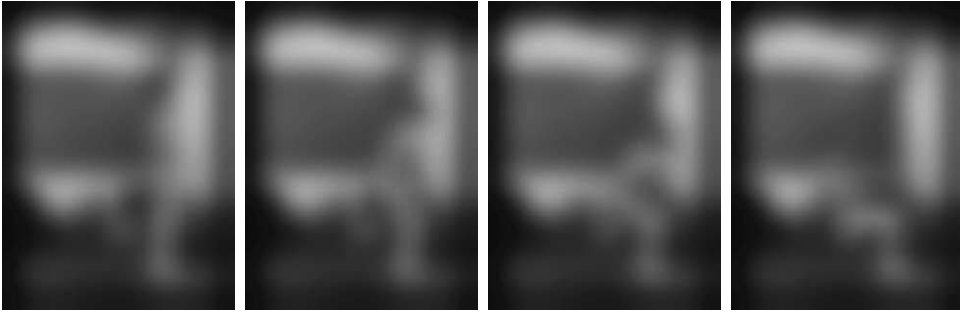


Figure 4.1 Four still frames cut from a video by Bobick and Davis (2001). Used with permission.
 NOTE: The video shows a person engaged in a common, everyday activity. The low-pass spatial filtering of video makes it difficult, from any individual frame, to discern the person, let alone what the person is doing. However, when the video is played at normal rate, the pattern of motions makes both the person and the person's action immediately apparent.

new techniques including brain imaging and transcranial magnetic stimulation have been deployed in concert with psychophysics to identify neural concomitants of motion perception in the human visual system.

Our goal in this chapter is to highlight some of these exciting developments. However, limitations on space—together with the exponential growth of the literature on motion perception—forced on us hard choices about what to include and what to omit. Thus, this chapter emphasizes motion in the front-parallel plane, unavoidably deemphasizing work on motion in depth and “cyclopean” motion perception (Patterson, 1999). In addition, the chapter focuses on motions of objects defined by luminance contrast, with little discussion of important work on the role of chromatic information in motion processing (Dobkins, 2000; Gegenfurtner & Hawken, 1996). The chapter slights numerous interesting and potentially informative illusions of motion (e.g., Hikosaka, Miyauchi, & Shimojo, 1993; Krekelberg & Lappe, 2001; Viviani & Stucchi, 1989). Moreover, our coverage primarily focuses on motion perception in primates, particularly *Homo sapiens*. Consequently, interesting work on motion perception in birds (e.g., Bischof, Reid, Wylie,

& Spetch, 1999; Wylie, Bischof, & Frost, 1998), fish (e.g., Albensi & Powell, 1998; Orger, Smear, Anstis, & Baier, 2000) and insects (e.g., Dror, O'Carroll, & Laughlin, 2001; Gabbiani, Mo, & Laurent, 2001) has been left out. Our chapter does include research on “atypical observers,” particularly individuals with diminished motion sensitivity consequent to brain damage.

Stimuli

In introducing the first edition of this handbook, Stanley Smith Stevens (1951, pp. 31–32) observed that “In a sense there is only one problem of psychophysics, the definition of the stimulus. . . . [T]he complete definition of the stimulus to a given response involves the specification of all the transformations of the environment, both internal and external, that leave the response invariant. This specification of the conditions of invariance would entail, of course, a complete understanding of the factors that produce and that alter responses.” We agree. As this chapter underscores, contemporary research on visual motion perception has advanced in large measure because researchers are able to generate and deploy suitable stimuli, including

innovative computer-generated animations, that simulate complex, real-life events.

Commenting on one aspect of this challenge, Graham (1965, pp. 579–580) cautioned that “we must take care that parameters are not confounded, a danger that arises only too readily from the fact that velocity itself involves the variables of distance and time. In any given experiment the variables of time, distance, interval between stimuli, and cycle of repetition of stimuli must be clearly analyzed before we can be confident that unequivocal conclusions may be drawn.”

Researchers have developed many clever ways around the confounds that Stevens warned against. Consider just two examples. Under normal circumstances, a visual target’s movement always involves a change of that object’s shape, position, or both. This confounding of motion and position change has made it difficult to connect psychophysical responses to motion alone. To break the confound, Nakayama and Tyler (1981) generated matrices in which black and white cells alternated at random. All cells in a row were shifted back and forth, left and right; with appropriate rates of shift, observers saw oscillatory motion. The cells were small (<3 minarc) and spatially quite dense. Moreover, because all cells of the same color were indistinguishable from one another, the positions of individual elements could not be tracked. Despite the absence of position information, observers could detect the oscillatory motion generated by shifts of pattern elements.

Consider a second example of a stimulus designed to test a hypothesis about motion perception. To explore how the visual system combines or segregates spatially intermingled motions in different directions, Qian, Andersen, and Adelson (1994) created displays whose every local region contained balanced, opposite directions of motion. The locally opposed directions tended to cancel one another, which caused observers to see no

overall motion. This chapter offers numerous other examples of complex stimuli specifically designed to probe particular aspects of motion perception.

Overview of Motion Processing Stages

Where appropriate, this chapter relates psychophysical results on motion perception to underlying neural mechanisms. An interest in establishing such connections drives much contemporary research into visual motion. For this reason, it will be helpful to provide a broad overview of the anatomy and physiology of those portions of the primate visual system explicitly involved in the analysis of motion information (see Figure 4.2); for a more detailed account, see Croner and Albright (1999).

Among the neurons in the visual systems of primates, cells selectively responsive to the direction of motion are first encountered in area V1, the primary visual cortex, which is located in the occipital lobe. Such neurons are often described as “tuned” for direction.³ Beginning with the landmark work of Hubel and Wiesel (1968), it has been known that a significant fraction of V1 neurons respond best when a contour moves through their receptive fields in a particular direction; responses are significantly diminished when movement is in the opposite direction. Different neurons have different preferred directions of motion, with all directions around the clock represented within the ensemble of neurons. This inaugural stage of processing comprises a local analysis of motion energy. In this analysis, direction-selective neurons act as filters that register the presence of component features of moving objects within

³As Parker and Newsome put it (1998, p. 229), “A neuron is considered to be ‘tuned’ if the response is strongest to a particular value (or narrow range of values) of the stimulus and declines monotonically as stimulus values depart from this ‘preferred’ value.”

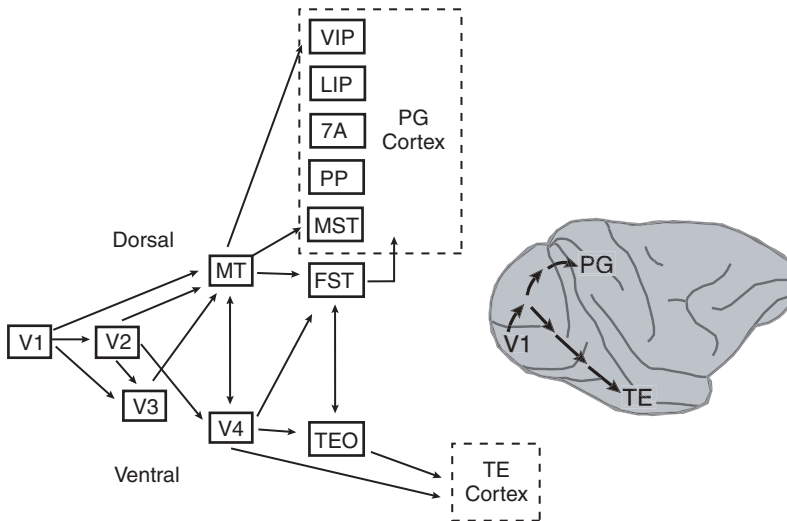


Figure 4.2 Diagram illustrating proposed functional and anatomical streams in the primate cerebral cortex.

NOTE: Partially separate streams carry information from area V1 either dorsally, toward the inferior parietal cortex (PG), or ventrally, toward the inferior temporal cortex (TE). Arrows indicate the main feedforward projections between areas. Abbreviations used in the diagram: V1, primary or striate cortex; MT, middle temporal area (also known as V5); VIP, ventral intraparietal; LIP, lateral intraparietal; PP, posterior parietal, MST, medial superior temporal; FST, fundus superior temporal; PG, inferior parietal cortex; TE, inferior temporal cortex.

SOURCE: After Ungerleider and Haxby (1994).

the local regions of their receptive fields (Emerson, Bergen, & Adelson, 1992).

The outputs of these local filters in area V1, in turn, activate second-stage analyzers that integrate motion signals over more extended regions of visual space. This second-stage analysis begins with neurons in the middle temporal visual area, or area MT, as it is typically called. Area MT receives some of its input directly from area V1 and the rest indirectly from area V1 via areas V2 and V3. Nearly all neurons in area MT are selective for the direction and speed of stimulus motion, again with the range of preferred directions among neurons spanning 360 degrees. MT neurons have larger receptive fields than do V1 neurons, which means that they can integrate motion signals over larger regions of visual space. Moreover, a given MT neuron will respond to motion in its preferred

direction regardless of whether those motion signals are carried by luminance, color, or texture. MT neurons, in other words, exhibit form invariance (Croner & Albright, 1999), implying that those neurons register motion information per se. MT neurons, in turn, project to higher visual areas that encode more complex forms of motion, including expansion and rotation (Tanaka & Saito, 1989) and motion-defined boundaries (Van Oostende, Sunaert, Van Hecke, Marchal, & Orban, 1997). Outputs from area MT also make their way to visual areas in the frontal lobe that are concerned with the control of eye movements (Bichot, Thompson, Chenchal Rao, & Schall, 2001; Schall, 2000).

A great many studies implicate area MT in the perception of motion. Though neurons in area MT certainly contribute to the perception of motion, it is clear that this is not the

sole site where neurons extract significant motion information. Actually, various aspects of motion perception depend on the neural computations carried out in different areas of the cortex. Normally, motion perception depends on activity distributed over many areas of the brain, each extracting somewhat different information from the retinal image. Complicating matters, in macaque monkeys, which have visual systems that are highly similar to those of *Homo sapiens*, back-projections from area MT to area V1 have been demonstrated (Beckers & Homberg, 1992). Initial evidence suggests that in humans this back-projection may be important for conscious awareness of visual motion. To explore this idea, Pascual-Leone and Walsh (2001) applied brief pulses of magnetic energy⁴ to spatially restricted regions of the scalps of human observers. This technique is known as transcranial magnetic stimulation (TMS). When the localized pulses are adjusted in duration, frequency, and amplitude and are delivered to particular regions of the scalp, TMS creates sensations of flashes of light. Called *phosphenes*, these flashes appear to move when the pulses are delivered to the scalp overlaying visual area MT, but they are stationary when TMS is delivered to the scalp that overlays area V1. By applying separate TMS pulses asynchronously to area V1 and area MT, Pascual-Leone and Walsh obliterated observers' conscious experience of the moving phosphenes that were ordinarily evoked by MT stimulation. This result

required the investigators to deliver TMS to area V1 some tens of milliseconds after area MT was stimulated. Presumably, the obliteration of motion perception is caused by a disruption of a re-entrant: back-projections from area MT to area V1. A similar result was reported by Beckers and Homberg (1992).

The preceding description of the motion pathway was based mainly on physiological and anatomical studies of nonhuman primates. During the past decade, understanding of motion perception's neuronal substrates in humans has been advanced significantly by the use of brain imaging techniques, primarily functional magnetic resonance imaging (fMRI). This growing literature has identified at least a dozen distinct regions in which neurons respond to visual motion. These regions in the human brain stretch from the occipital lobe to the frontal lobe (Culham, He, Dukelow, & Verstraten, 2001; Sunaert, Van Hecke, Marchal, & Orban, 1999). Among the regions responsive to motion are area V1 (which responds to almost any moving pattern, as well as to stimulus flicker) and the MT/medial superior temporal (MST) complex, located on the brain's lateral surface near the junction of the occipital, parietal, and temporal lobes. This region, which we shall refer to as MT+, responds weakly to flicker but strongly to coherent motion, including optic flow patterns (discussed later). Other important motion areas include area KO (for kinetic occipital), which responds preferentially to motion-defined boundaries, and area STS (for superior temporal sulcus), which is especially responsive to patterns of motion that portray biological motion. As appropriate, brain imaging results are introduced throughout this chapter to clarify the neural computations that make motion perception possible.

With this overview in place, we can now explore several aspects of motion perception that make it so crucially important for guidance of people's everyday activities.

⁴TMS offers a powerful tool for investigating cognitive or perceptual neural circuitry (Pascual-Leone, Walsh, & Rothwell, 2000), including circuitry that supports various aspects of motion perception (e.g., Hotson & Anand, 1999; Walsh, Ellison, Battelli, & Cowey, 1998). When the TMS coil is positioned against an observer's skull, a powerful, focused magnetic field hits and penetrates the skull. The field penetrates superficial layers of the cerebral cortex, and can temporarily terminate or modify currently ongoing neural activity or alter neural activity that is about to begin.

THE LIMITS OF MOTION PERCEPTION

Motion Detection

Visual motion can be construed as an event that unfolds over space and time. Distilled to the simplest case, motion involves a continuous change in the spatial position of a single object over time; this can be depicted in the form of a space-time plot in which spatial position along one dimension is plotted as the function of time in Figure 4.3. Intuitively, one might expect that the ease with which this kind of simple event can be seen would depend on the magnitude of the displacement over time and on the rate at which that

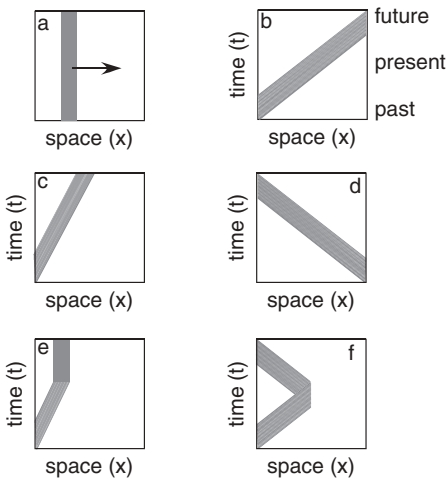


Figure 4.3 Illustrative space-time (x - t) diagrams that are used to represent motion.

NOTE: Panel A: Vertical bar moves rightward at constant speed. Panel B: The space-time representation of the movement in Panel A. Panel C: Space-time representation for bar moving rightward at higher speed than in Panel A. Panel D: Space-time representation for bar moving leftward at same speed as in Panel A. Panel E: Space-time representation for bar that moves rightward, stops suddenly, and remains stationary. Panel F: Space-time representation for bar that moves rightward and then abruptly reverses direction.

displacement occurred. There is truth to this intuition. Consider, for example, the movement of a clock's minute hand. People cannot see the clock hand's gradual progression, but intuitively we know that it has moved because its position has changed over time. Motion perception, however, need not involve any kind of intuitive process; motion is a direct experience, uniquely specified by the visual system (Exner, 1888; Nakayama, 1981; Thorson, Lange, & Biederman-Thorson, 1969). But how sensitive is the system that generates this experience? What is the lower limit for detection of motion? Measurements with a single moving object show that an object must traverse at least 1 minarc for a sensation of motion to be experienced. (This distance is approximately the edge-to-edge lateral separation between adjacent alphanumeric characters on this page when viewed at arm's length.) This value varies, however, with the object's duration, velocity, and luminance, as well as with the region of the retina stimulated. An up-to-date summary of this literature is given by Tayama (2000).

Very seldom, however, are people called upon to detect the motion of a single object appearing in isolation. Instead, most everyday detection of motion involves the detection of an object's (or a group of objects') motion *relative* to another object (or another set of objects). And at this challenge—detecting relative motion—humans excel. We are vastly better at detecting relative motion than we are at detecting absolute motion (e.g., Leibowitz, 1955). This is strikingly demonstrated in a study by Lappin, Donnelly, and Kojima (2001) in which observers viewed an array of three horizontally aligned “blobs” (circular, Gaussian luminance patches). In one condition, all three blobs moved laterally back and forth in unison (in-phase motion), and in another condition the center blob's direction of motion was opposite to that of the flanking blobs (antiphase, or relative, motion).

Motion acuity—the smallest detectable motion displacement—was actually better for the antiphase condition compared with the in-phase condition. In other words, tiny motion displacements visible in the antiphase condition were impossible to see when there was no relative motion. This finding dovetails nicely with earlier results showing that humans are keenly sensitive to shearing motion (Nakayama, 1981; Snowden, 1992), which also entails relative motion instead of overall rigid displacement. This direction contrast amplifies differences in motion vectors in neighboring regions of the visual field. One must keep in mind that in the research described later, motion performance is measured for moving targets that appear within some background framework.

Intuition suggests that motion might render an object less detectable. (Consider, for example, the difficulty that a person experiences when trying to read a newspaper in a moving subway.) Under most circumstances, however, exactly the opposite is true. Especially for objects with significant energy at low spatial frequencies, motion can render an otherwise invisible object visually conspicuous (Robson, 1966). To experience this for yourself, hold an object between the uniform surface of a wall and a light source in order to create a large, very faint shadow on the wall. When the nonmoving dim shadow fades to invisibility, move the occluding object and notice how the shadow abruptly springs into existence. The familiar textbook example of seeing the retinal blood vessels in your own eye by jiggling (i.e., moving) a light source on your sclera is another instance of motion's ability to reveal what otherwise would have been undetectable.

To characterize more precisely the optimal stimulus for the motion system, researchers have exploited the lower envelope principle. Barlow first called attention to the principle 40 years ago and most recently framed it this

way: “Sensory thresholds are set by the class of sensory unit that has the lowest threshold for the particular stimulus used and are little influenced by the presence or absence of responses in the enormous number of other neurons that are less sensitive to that stimulus” (Barlow, 1995, p. 418). Discussing various applications of the principle to sensory systems, Parker and Newsome (1998, p. 242) noted that “in its pure form, the lower envelope principle means literally that a single neuron governs the behavioral threshold. The development of the lower envelope principle has been very much a reaction by neurophysiologists to the formerly prevalent notion that single neurons are inherently unreliable devices.”

In an attempt to apply the lower envelope principle to motion, Watson and Turano (1995) measured the minimum contrast at which observers could discriminate direction of movement. Their test stimuli were drawn from a family of patterns known as Gabor functions. Each Gabor function comprises a sinusoidal grating that has been multiplied, point by point, by the values of a two-dimensional Gaussian function. This multiplication modulates the sinusoid's contrast, producing a pattern whose contrast falls off smoothly in all directions from a maximum at the pattern's center.⁵ In search of the most easily seen moving stimulus, Watson and Turano independently varied the spatiotemporal characteristics of both the sinusoidal grating and its modulating Gaussian function. The stimulus yielding the lowest contrast threshold was a sinusoidal grating with spatial frequency of 3 cycles/degree and drift rate of 5 Hz, with a width and height of 0.44 degrees

⁵These functions bear the name of Dennis Gabor, a Hungarian engineer and applied physicist. Gabor won the 1971 Nobel Prize in Physics for his work on wavefront reconstruction in optical holography. In vision research, Gabor functions are used as stimuli; also, they are good approximations to the spatiotemporal receptive fields of many visual neurons.

visual angle and a duration of 0.13 s. Applying the lower envelope principle, these parameters describe the most sensitive of the neural filters in the direction-extracting system.

Stimuli like those used by Watson and Turano (1995) and others have the advantage of limiting stimulus energy to particular bands of spatial and temporal frequencies. Although such grating patterns are often used to explore motion perception, they bring some disadvantages. For example, they confound motion with orientation and can appear to move only in the directions perpendicular to their orientation. To get around these limitations, researchers devised an entirely different class of motion stimuli, arrays of irregularly spaced moving elements such as blobs or dots. These computer-generated stimuli are commonly known as random dot cinematograms (RDCs), and there are several different algorithms for generating them. Distilled down to their essence, most RDCs consist of “signal” dots that move in a given direction (or within a given range of directions) and are intermingled randomly with “noise” dots that move in random directions.⁶ When the proportion of signal dots is high, dots in the RDC appear to move coherently in the general direction of those signal dots; when signal dots comprise only a small fraction of the RDC, the sense of motion coherence is weak or, in the limit, absent entirely. Motion threshold is defined as the minimum percentage of signal dots necessary for detection of coherent motion. It should be stressed that the information supporting de-

tection performance in these stochastic stimuli must be extracted globally: Observers cannot perform well simply by attending to a single dot or to a restricted region of the display.

Humans exhibit remarkable sensitivity to coherent motion in RDCs. Under optimal conditions, observers can detect signal percentages as small as 5% (Scase et al., 1996), and this holds for signal dots portraying translational motion, rotational motion, and expansion and contraction (but see Ahlström & Börjesson, 1996; Blake & Aiba, 1998). Absolute threshold values vary with display size (Burr, Morrone, & Vaina, 1998), dot density (Watamaniuk, 1993), and exposure duration (Watamaniuk, Sekuler, & Williams, 1989), but not with direction of motion (Gros, Blake, & Hiris, 1998). Visual cues that allow segmentation of signal dots from noise dots—such as color or contrast polarity—can substantially enhance detection of motion (Croner & Albright, 1997). Prior exposure, or adaptation, to strongly coherent motion in a given direction temporarily elevates coherence thresholds for directions of motion within roughly 40 degrees of the adapting direction, with the elevation in threshold being largest at the adapting direction. Thresholds are also affected by higher-order variables such as visual attention to a particular direction of motion (Raymond, 2000; Raymond, O’Donnell, & Tipper, 1998), a point discussed later in this chapter.

In an influential series of experiments, Newsome and colleagues used RDCs to test motion detection in monkeys. They recorded neural responses from single cells in areas MT and MST of the monkey’s brain while the monkey tried to detect motion (see a review of this work by Parker and Newsome, 1998). In general, the monkey’s behavioral threshold for detecting motion was very close to the neural threshold derived for some individual directionally selective neurons. The

⁶The terms *signal* and *noise*, commonplace in psychophysics, derive from engineering and communication sciences. There, the task facing a biological or machine detector is portrayed as the extraction of a message (signal) from a stream of input, some portion of which (noise) is irrelevant or even antithetical to the extraction of the message. These definitions enable investigators to characterize a detector’s sensitivity in terms of the ratio of signal to noise that just allows signal extraction.

correspondence between neural thresholds and behavioral thresholds points to a tight linkage between neural activity in areas MT and MST and the monkey's performance, with "neural" thresholds corresponding closely to behavioral thresholds (Celebrini & Newsome, 1994; Newsome, Britten, & Movshon, 1989).

This linkage was further strengthened by the finding that electrical stimulation of neurons in area MT (Salzman, Murasugi, Britten, & Newsome, 1992) or in area MST (Celebrini & Newsome, 1994) can bias a monkey's perceptual report of motion direction in RDCs. Thus, direct stimulation of MT neurons tuned to leftward motion increased the probability that the RDC would appear to move in that direction. Direct electrical stimulation of particular clusters of MT neurons, then, was perceptually equivalent to the effect normally produced by an RDC moving in the neurons' preferred direction with a particular coherence level. Lesion studies lend additional support to the idea that area MT participates in motion perception. Lesions encompassing area MT, area MST, or both areas produce permanent impairments in the ability to extract coherent motion from RDCs (Newsome & Paré, 1988; Rudolph & Pasternak, 1999). Comparable deficits in motion sensitivity to RDCs are found in human patients with damage to an area of the brain homologous to area MT in primates (Schenk & Zihl, 1997).

Trajectory Detection

Algorithms that generate RDC stimuli ordinarily prevent any signal dot from moving in a constant direction throughout the entire animation sequence. This is done to prevent observers from basing judgments on any single dot's trajectory, instead forcing judgments to arise from the integration of many motion vectors. In the natural environment, however, there are many instances in which it is important to detect one object's movement in the

presence of other, distracting moving objects, and, for that matter, despite temporary occlusions in the target object's path. To take an unpleasant example, a lion in hunting mode can visually track the path of one particular zebra in a herd, even when all other members of the herd are moving about in random directions, and even though the target zebra is temporarily obscured by vegetation or other opaque objects. To learn how vision manages such feats, Watamaniuk, McKee, and Grzywacz (1995) measured observers' abilities to detect the presence of a single dot moving on a fixed straight path in a field of noise dots whose directions changed randomly over time. The signal dot was identical to the noise dots in luminance, size, and speed. For a stimulus duration of 500 ms, motion was detected 90% of the time, even when there were as many as 250 noise dots. Under such conditions, the proportion of signal dots was minute: only 0.4%.

Watamaniuk and McKee (1995) also found that a single moving dot's trajectory is easily seen even when that trajectory is interrupted by a series of opaque occluders (Figure 4.4). Detection of the dot's motion across three path segments, each separated by an occluder

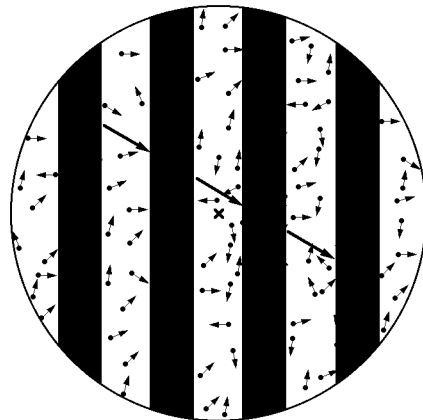


Figure 4.4 Diagram of display used by Watamaniuk and McKee (1995) to examine effects of occlusion on trajectory detection.

NOTE: See text for further details.

1 degree wide, was essentially as good as detection of the same motion over a single uninterrupted path of equivalent length. Therefore, the motion signal generated by the moving object was essentially unaffected by temporary interruptions of that signal when the object was occluded. However, when the dot's trajectory was momentarily interrupted by a different kind of occluder, detection of the moving dot fell dramatically. Here, occluding regions were filled with random-direction motions (noise) similar to the random motions in the display's other regions. The dot disappeared when it entered a noisy occluding region and reappeared when it left that region. Within each noisy occluder the virtual path of the signal dot was probably masked or distorted by similarly directed motion vectors in the noise. These noise directions led the directional signal astray, reducing the precision of matches from one segment of the dot's trajectory to the next. (This is an instance of the so-called motion correspondence problem, which is discussed in a subsequent section.) Because the reduction in detectability persisted even when noise-filled occluders lay in a depth plane different from the regions containing the trajectory, it seems that trajectory detection operates prior to the assignment of depth to image components.

Grzywacz, Watamaniuk, and McKee (1995) proposed a model that can account for many observations on trajectory detection. In their model, local connections among motion mechanisms enhance responses that result when mechanisms are stimulated in sequence and roughly in the direction of their directional tuning. These connections are spatiotemporal analogues to the spatial association fields that have been implicated in contour integration (Field, Hayes, & Hess, 1993; Geisler, Perry, Super, & Gallogly, 2001; Sigman, Cecchi, Gilbert, & Magnasco, 2001). From a perceptual perspective, the connections postulated by Grzywacz et al. promote

what Gestalt psychology dubbed "good continuation": Perception will favor trajectories that are smooth over trajectories that have large and abrupt changes in direction. Such spatiotemporal preferences were demonstrated in Metzger's (1934) observations with objects moving on independent but intersecting paths.

Because of the spatiotemporally tuned local connections in Grzywacz et al.'s (1995) model, each successively stimulated motion mechanism will produce a response that is larger than that produced by the previously stimulated mechanism. Eventually, the response grows large enough to be accurately detected, even though other motion detectors are responding to the background motion noise. Because local connections involve mechanisms with a range of similar directional tuning (spanning about ± 30 degrees), the model can account also for the detection of curved trajectories as well as straight ones (Grzywacz et al., 1995; Verghese, Watamaniuk, McKee, & Grzywacz, 1999).

Grzywacz et al.'s (1995) trajectory network model postulates facilitation of signals in sequentially stimulated motion mechanisms, a result observed by Verghese et al. (1999), who compared the detectability of two kinds of trajectories. In one, the moving elements followed a single continuous trajectory of length L ; in the other, the same elements traced out n separate trajectories, with a gap between successive segments. Because each segment was L/n long, their summed lengths were the same as the length of the single uninterrupted trajectory. Verghese et al. wanted to know how the motion system would sum the motion signals contained in these segments. For a computational benchmark, they drew upon the notion of probability summation. In its simplest form, probability summation predicts that detection of a signal should be equal to the sum of the square of the number of independent stimulus elements (Graham, 1989; Watson,

1979). In Verghese et al.'s experiments, the number of independent stimulus elements is n . This computational rule gave a good account of detection when trajectory segments were so short that each segment was likely to be detected by only a single mechanism. With longer trajectories, however, probability summation failed badly. For example, a single 200-ms trajectory was approximately three times more detectable than were two spatially isolated 100-ms trajectories presented one after another, which kept L constant. Thus, the detection of an extended trajectory cannot be explained by activation of a series of independent motion detectors whose outputs are summed linearly. Instead, the result points to significant spatiotemporally tuned interactions among local motion units, of the kind postulated in Grzywacz et al.'s trajectory network model.

Motion Discrimination: Direction, Speed, and Coherence

Having highlighted key determinants of motion detection, we turn now to motion discrimination. In tasks used to measure discrimination, observers must not only detect the motion (i.e., see that motion is present) but also judge one or more of the motion's essential characteristics, such as direction, speed, or coherence.

In experiments on motion perception, sinusoidal grating stimuli were used to investigate *discrimination* of direction of motion at or near the contrast *detection* threshold for that moving stimulus. In general, the contrast at which observers could just detect the presence of a moving stimulus was also sufficient to identify its direction of motion (Derrington & Henning, 1993; Levinson & Sekuler, 1975; Watson, Thompson, Murphy, & Nachmias, 1980). Such results suggested that visual mechanisms that extract motion signals are labeled for direction. In this

context, a neural mechanism is said to be labeled for some elementary sensation, Φ , if activity in the mechanism is sufficient to generate the experience of Φ (Watson & Robson, 1981). Although much has been learned about motion from experiments using grating stimuli, an exclusive reliance on such stimuli encounters substantial limitations. If an observer cannot see the ends of the grating (the usual case in motion experiments), unambiguous motions can be produced only in the two directions orthogonal to the grating's orientation, an ambiguity known as the aperture problem (discussed later). Thus, creating other directions of motion requires a change in the orientation of the grating, thus confounding direction and orientation. Partly to avoid this potential confound, Westheimer and Wehrhahn (1994) measured direction discrimination for a single moving spot. They found that at high speeds (30 deg/s) direction discrimination was equal to that for orientation discrimination of a static line of the same length as the distance traveled by the moving spot and presented for the same duration. This suggests that at high speeds the moving spot created an oriented smear (a virtual line) on which observers could have based their judgments (work by Geisler, 1999, makes a similar point). This potential problem is avoided, however, by using RDCs in which the directions of individual dots change frequently or in which each dot has a limited lifetime.

Williams and Sekuler (1984) created RDCs in which individual elements were assigned new directions of motion in each frame. When directions were drawn from a distribution of directions spanning 180 degrees or less, observers saw the entire fields of dots move in the direction of the distribution's mean, even though the random movements of individual dots were also visible. This meant that the motion mechanisms responsible for this global motion integrated direction information over much of the motion display, if not over the

entire display. Using a RDC in which each dot chose a new direction of motion each frame from a distribution of directions spanning 30 degrees, Ball, Sekuler, and Machamer (1983) determined that the direction tuning of these motion mechanisms is broad: Two directions of motion had to be separated by 120 degrees before they no longer stimulated the same mechanism.

With such broadly tuned motion mechanisms to draw upon, how well can observers discriminate small differences in direction? To answer this question, Watamaniuk et al. (1989) measured direction discrimination for fields of random dots. When all dots moved in the same direction, observers reliably discriminated directions that differed by only 1 degree. Moreover, this threshold was relatively resistant to the inclusion of random motions that potentially interfere with signal extraction. When similar measures were made with RDCs whose elements moved in a range of directions, once the range of directions in the RDC exceeded 30 degrees, direction discrimination thresholds increased with direction range. In addition, direction discrimination improved as exposure duration lengthened, up to at least 300 ms to 400 ms, and as size of the stimulus increased, up to at least a 10-degree diameter (Watamaniuk & Sekuler, 1992; Watamaniuk et al., 1989). Thus, the motion system is robust in the presence of random motions, and it can produce precise discriminations using mechanisms that are broadly tuned.

RDCs can generate motion percepts simultaneously on two different spatial scales. In particular, the perception of global flow can coexist with the perception of the small random motions of individual dots. Watamaniuk and McKee (1998) showed that direction information was encoded independently on the two spatial scales, global and local. In their RDCs, a single central dot moved in a constant direction while the remaining 100 to

150 dots were assigned a new direction of motion in each frame from a distribution spanning 160 degrees. The direction of global flow and the direction of the constant-direction dot were always similar, but both varied from trial to trial. After a brief presentation of the RDC, a tone told the observer which motion, global or local, was to be judged. Under these conditions, observers judged either direction just as well as if they had been told in advance which direction to judge. This suggests that visual information on different spatial scales is processed simultaneously with little interference.

As indicated earlier, motion detection is isotropic. For direction discrimination, however, performance is anisotropic, varying strongly with the test direction. Discrimination thresholds are lowest (i.e., performance is best) for directions at and near the “cardinal” directions of up, down, left, and right (Gros, Blake, & Hiris, 1998). This oblique effect could reflect a disproportion in the number of neurons tuned to cardinal directions; alternatively, it could arise from narrower directional tuning for neurons tuned to cardinal directions. The absence of an oblique effect for the *detection* of motion suggests that the second interpretation is correct, but the question remains open.

Direction Change

In the natural world, objects often change direction, and responses to such changes can be quite important. For example, direction changes by inanimate objects may result from a collision; direction changes by living creatures may convey biologically significant information, such as the information produced by a series of hand gestures. Direction-tuned neurons in area MT of primate cortex have been shown to be efficient encoders of such changes (Buracas, Zador, DeWeese, & Albright, 1998). Synchronized changes in

direction of motion among an array of small objects promote perceptual grouping of those objects into a coherent shape (Lee & Blake, 1999).

Dzhafarov, Sekuler, and Allik (1993) proposed a formal computational model for responses to changes in speed and direction of motion. The model, which has been extended by Mateeff, Genova, and Hohnsbein (1999), incorporated a process that normalized all stimulus velocity signals registered prior to any change.⁷ Velocity normalization is an instance of visual adaptation processes that reduce redundancy in neural responses by minimizing the total neural activity elicited by any stimulus input (Barlow, 1990). For Dzhafarov et al.'s implementation, assume that some stimulus has an initial velocity V_0 , which changes abruptly to a different velocity, V_1 . As a result of normalization, this change from V_0 to V_1 is detected as though the change were the onset of an initial motion with velocity $|V_1 - V_0|$. In other words, the actual value of V_0 is irrelevant; all that matters is the absolute difference between V_1 and V_0 . This basic computation successfully predicted observers' speeds of response to change with a considerable variety of values for V_0 and V_1 . A. B. Sekuler and R. Sekuler (1993) examined this normalization process further. In an attempt to disrupt the extraction of information about V_0 , they injected transients such

as temporary occlusion or disappearance into the trajectory prior to the change to V_1 . By injecting a transient at various times during and after V_0 , they were able to interrupt or freeze normalization. Even a relatively brief disappearance of the moving target reset normalization entirely, erasing all the velocity information that had been extracted up to that point.

Speed Discrimination

During their daily routines, humans frequently make judgments about the speeds of moving objects. Consider, for example, the simple acts of judging the speeds of nearby cars when changing lanes on the highway or running across the lawn to intercept a small child who is crawling toward a street. How do humans judge speed in these kinds of situations? Because objects moving at different speeds cover different distances in any given temporal interval, observers could use distance traveled as a cue to speed. Alternatively, the time needed to travel some criterion distance might also be used as a cue to speed. So how can one measure speed discrimination without confounding influences of time and distance? The usual experimental approach is to randomize presentation time over a range so large that duration and therefore distance cues become unreliable (McKee & Watamaniuk, 1994).

Speed discrimination thresholds are typically presented as Weber fractions ($\Delta V/V$) that specify the proportional difference in speed needed to produce reliable discrimination. The smallest increment in speed that can be reliably detected (ΔV) is divided by the mean or base speed (V). Most studies have reported Weber fractions in the range 0.04 to 0.08 with various types of stimuli, including moving lines, dot fields, and sinusoidal gratings (Bravo & Watamaniuk, 1995; Brown, 1961; De Bruyn & Orban, 1988; McKee, 1981;

⁷Normalization refers to various linear operations that transform some data set, \mathbf{D} , into a new set, \mathbf{D}' , while preserving particular types of numerical relationships among the set's members. Of two common forms of normalization, subtractive normalization of \mathbf{D} can be described as $\mathbf{D}' = \mathbf{D} - k$; divisive normalization is represented by $\mathbf{D}' = \mathbf{D}/k$. Subtractive normalization, which is the form used in Dzhafarov et al.'s model, preserves the relative magnitudes of members of \mathbf{D} ; divisive normalization preserves the proportional relationships among members of \mathbf{D} . Heeger (1994; Heeger, Simoncelli, & Movshon, 1996) describes another type of normalization, which operates in the visual cortex to suppress partially the responses of individual neurons.

Nakayama, 1981; Orban, de Wolf, & Maes, 1984; Pasternak, 1987; Turano & Pantle, 1989; Watamaniuk & Duchon, 1992). The Weber fraction's constancy means that the smallest detectable increment in speed increases with the base or starting speed.

Although the Weber fraction for speed discrimination is fairly constant over a variety of test conditions, perceived speed can be altered by any number of stimulus parameters. For example, Katz, Gizzi, Cohen, & Malach (1990) reported that drifting stimuli that are only briefly presented appear to move faster than do stimuli that are presented for longer durations. A grating's drift or movement rate takes degree/second as its units, where "degree" signifies degrees of visual angle. It is important to distinguish drift rate from a related variable, temporal frequency, which takes units of Hz or, equivalently, cycles/s. The relationship between a grating's drift rate and the temporal frequency produced by that drift takes account of the grating's spatial structure:

$$\begin{aligned} \text{Temporal frequency (Hz)} \\ &= \text{Drift rate(deg/s)} \\ &\quad \times \text{Spatial frequency (cycles/deg)} \end{aligned}$$

Perceived speed of movement (perceived drift rate) varies with a grating's spatial frequency, which takes units of cycles/degree. Sinusoidal gratings presented at lower temporal frequencies (and hence lower spatial frequencies) appear to be slower than gratings moving at the same speed but with higher temporal frequency (Diener, Wist, Dichgans, & Brandt, 1976; McKee, Silverman, & Nakayama, 1986; Smith & Edgar, 1991). Turning to other variables that affect perceived speed, when gratings of different contrast move at the same physical speed, a lower-contrast grating appears to move more slowly (Stone & Thompson, 1992; Thompson, 1982). Furthermore, objects seen in the periphery appear to move more slowly than do foveal objects of

the same speed (Johnston & Wright, 1986; Tynan & Sekuler, 1982). Finally, the perception of an object's speed is adversely affected at low luminance levels, which correspond to rod-mediated, scotopic vision. Gegenfurtner, Mayser, and Sharpe (2000) showed that a moving object's perceived speed is considerably slowed in rod-mediated vision, compared to its perceived speed in cone-mediated vision. To understand the likely basis for this result, note that differences in constants of rod time and cone time indicate that rods average information over longer periods than do cones. Gegenfurtner et al. speculated that the rods' extended temporal averaging attenuates motion signals that would be generated in detectors that are tuned to high velocities. The reduction in such signals causes the reduction in perceived speed under rod-dominated conditions. Grossman and Blake (1999) found that the perception of biological motion and structure from motion were also impaired under scotopic viewing conditions. Such findings have clear implications for driving safety at night on poorly illuminated roads.

IDEAL OBSERVERS AND MOTION ANALYSIS

Early studies established that the visual system was an extraordinarily efficient detector of light (Hecht, Schlaer, & Pirenne, 1942; Rose, 1948). To assess the efficiency of vision when it performs other tasks, researchers often turn to ideal-observer models. In its most common form, an ideal observer comprises a mathematical model of a theoretical observer who has complete and perfect knowledge of all relevant stimulus and task statistics; in addition, this theoretical ideal makes statistically optimal decisions when transforming sensory information into psychophysical responses. Ideal-observer models afford interesting benchmarks for the fallibility of

human observers, in comparison with the theoretical limit represented by an ideal observer. Ideal observer models have been used to compare human and ideal performance for tasks such as detecting changes in spatial patterns (e.g., Barlow, 1978; Barlow, 1980; Barlow & Reeves, 1979; Burgess & Barlow, 1983; Burgess, Wagner, Jennings, & Barlow, 1981; van Meeteren & Barlow, 1981).

Random and unpredictable variability in the stimulus limits an ideal observer's performance because it subverts the observer's otherwise perfect knowledge of the stimulus to be detected. Such random variability is known as noise.⁸ Ideal-observer models try to predict how humans and ideal observers might perform when each must extract information from a noisy stimulus. Increasing stimulus noise leads any observer—human as well as ideal—to make more errors, such as failures to detect the stimulus, misclassifications of a stimulus, or declarations that a stimulus is present when it actually is not. How closely a human observer approximates the theoretical ideal defines the human observer's efficiency. This statistic is given by the square of the ratio of human performance to ideal performance, where both performance measures are expressed as d' values (Chap. 2, Vol. 4 of this series). Thus, if a human observer's performance is ideal, efficiency is 1.0. Detailed

comparisons of human and ideal observers create valuable diagnostic opportunities for identifying and quantifying components that limit human performance (Geisler, 1989).

In the first application of ideal-observer analysis to visual motion perception, Watamaniuk (1993) devised an ideal-observer model that discriminated the direction of global flow generated in RDCs. In specially constructed RDCs, the directions in which each dot moved over successive frames were chosen randomly, with replacement, from a Gaussian distribution of directions. The unusual algorithm for generating the movements or elements made the stimulus noisy: The algorithm introduced a random discrepancy between the actual directional content of the stimulus and the nominal, or average, directional content represented by the sampled distribution. To vary the magnitude of this discrepancy, in different conditions directions were drawn from one of five Gaussian distributions with different standard deviations. The larger the standard deviation, the greater the mean absolute discrepancy between actual and nominal-direction information in the stimulus. This introduced random sampling noise into the stimuli. Because the ideal observer had to rely on its knowledge only of the *nominal* stimulus, introduction of variability (noise) into the *actual* stimulus reduced the observer's performance.

Direction discrimination was measured for each direction distribution for a range of stimulus durations, stimulus areas, and spatial densities of dots. As expected, human performance was always poorer than the ideal observer's performance. Efficiency generally decreased with increased stimulus area or density and remained constant as duration increased from 100 ms to 500 ms. However, the data clearly showed that efficiency increased as stimulus noise increased, reaching averaged values of 0.35. This suggests that the human visual system was influenced

⁸In virtually any psychophysical experiment, valuable information can be gained from measurements made with stimuli to which various amounts of noise have been added (Pelli & Farell, 1999). Noise can assume different forms, depending on the observer's task. For example, when the task involves detection of a static form, the noise usually comprises independent, random luminance values added to each element in the stimulus display (Bennett, Sekuler, & Ozin, 1999; Gold, Bennett, & Sekuler, 1999); when the task involves detection of symmetry in a pattern, noise may be introduced by randomly altering the position of each of the pattern's elements (Barlow & Reeves, 1979); or, when the task requires identification of global motion direction in an RDC, noise can be generated by randomizing the directions comprising the RDC (Watamaniuk, 1993).

by the random noise less than the ideal observer was. Note that high efficiency does not mean high level of performance. Because efficiency is a ratio of human performance to ideal performance, high efficiency can be obtained at any level of performance. In fact, Watamaniuk (1993) found highest efficiency for direction discrimination when average performance was at a d' of about 0.75, which translates to a percent correct discrimination of about 70%. Finally, Watamaniuk identified several factors that undermine human performance, including the limited spatial and temporal summation of human vision.

Watamaniuk's (1993) ideal observer was designed to *discriminate* one motion from another, but a comparable ideal observer could be designed for another task: to *detect* motion. Because the visual system exploits a different source of neural information both for direction discrimination and for motion detection (Hol & Treue, 2001), specifying an ideal-observer analysis for a new task can be far from a trivial matter. Barlow and Triparthy (1997) applied an ideal-observer analysis to the detection of coherent motion embedded in random motion noise. Human as well as ideal observers received two-alternative forced choice tests. They had to identify which of two intervals contained coherent motion rather than completely random directional noise. Noise was introduced into the stimulus by making the frame-by-frame positioning of the coherently moving dots less precise. As precision declined, efficiency increased, reaching values of approximately 0.3. This result points to the relatively coarse spatial resolution of human vision and shows that adding spatial position noise affects the ideal observer more than it affects the human. This coarse spatial resolution represents a low-pass spatial filtering operation, which, as Barlow and Triparthy speculated, enhances sensitivity to naturally occurring motion.

Extending this analysis of motion detection, Baddeley and Triparthy (1998) examined some limitations that might possibly undermine the performances of human observers. Using a novel statistical procedure that examined the frame-by-frame movements of each dot, Baddeley and Triparthy determined that whereas an ideal observer bases decisions on the motions of all dots in the display, human observers seem to use only a proportion of the dots in the display. The same frame-by-frame analysis allowed them to rule out other possible limiting factors, including the idea that human observers differentially weighted directional information generated at various locations in the visual field.

OPTIC FLOW AND STRUCTURE FROM MOTION

Motion affords potentially powerful information about the three-dimensional shapes of moving objects as well as about an observer's own movements within the environment populated by those objects. In particular, the movements of objects within an environment create spatiotemporal changes in the light distribution on the retina of a stationary observer. Likewise, an observer's movements through a stationary environment change his or her own retinal images. Such spatiotemporal changes, whatever their origin, are termed *optic flow*, and they constitute significant sources of visual information. For example, optic flow provides information about the speed, direction, and path of an observer's movements; it can also provide information about the three-dimensional structure of the environment (Koenderink, 1986). In the natural environment, an otherwise camouflaged object—such as an edible insect—stands out conspicuously when it moves relative to its background. Any creature that possesses the neural machinery to extract and reg-

ister the presence and shape of this target can secure a meal courtesy of visual motion.

Historically, research on optic flow has tended to bifurcate into distinct branches. One branch has focused on the use of optic flow in steering an observer's movement and heading; the other branch has focused on the use of optic flow in revealing the shape and structure of moving objects. In discussing the uses of optic-flow information, we will respect this bifurcation, but it is worth remembering that both uses of optic flow arise ultimately from the same source.

Optic Flow Supports Perception of Heading

Conventionally, the patterns of retinal image flow produced by self-motion are represented by an instantaneous velocity field, as illustrated for simple translatory movement in the top panel of Figure 4.5. Each vector signifies the velocity (direction and speed) in the retinal image of an environmental element. For the case illustrated, the observer's gaze is assumed to coincide with the direction in which the observer is moving. This creates a radial pattern of optic flow in which the focus of the flow corresponds to the observer's heading. Note that the representation contains no information about the physical attributes of the elements, such as their color, shape, and size. Instead, they are treated as uniform entities, known as *tokens*. The lower panel of Figure 4.5 represents the velocity field resulting from an observer's circular movement parallel to the ground plane. This velocity field would be generated, for example, on the retina of a driver whose automobile made a smooth turn.

Although snapshot representations like those in Figure 4.5 omit information such as acceleration-produced changes or temporary occlusions (Warren, Blackwell, Kurtz, Hatsopoulos, & Kalish, 1991), they are still

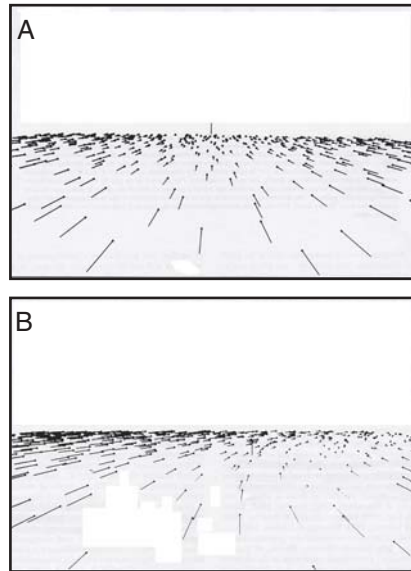


Figure 4.5 Optic-flow patterns.

NOTE: Panel A: Optic-flow pattern produced when an observer translates along a straight path; diagram assumes that observer is directed toward destination point. Panel B: Optic-flow pattern produced when an observer translates along a curved path.

SOURCE: From Warren, Blackwell, and Morris (1988). Used with permission.

useful in understanding optic flow's possible role in steering and wayfinding. Koenderink (1986) provided a thorough and accessible mathematical account of the optic-flow dynamics that result from various basic types of observer movement. Transformations generated by such movement, no matter how complex, can be decomposed into four basic components: translation, isotropic expansion, rigid rotation, and shear. Summing these basic components in varying amounts can reproduce the original complex optic-flow field. As a result, visual mechanisms specialized for extracting these basic components could generate signals that, in aggregate, would represent the complex flow field and, therefore, an observer's movements. The receptive field properties of neurons in area MST make those

neurons well suited to extracting optic-flow information related to an observer's heading. The participation of such neurons in navigation has been confirmed empirically. Direct electrical stimulation of local clusters of neurons in area MST of monkeys altered the monkeys' judgments of heading direction (Britten & van Wezel, 1998). With human observers and human brains, functional neuroimaging reveals large areas of MT+ that respond to particular components of optic flow—such as either circular or radial motion—but not to simple translation motions in a front-parallel plane (Morrone, Tosetti, Montanaro, Fiorentini, Cioni, & Burr, 2000).

Research into optic flow's role in wayfinding has addressed two key issues. First, psychophysical experiments had to determine whether observers could extract heading information from displays containing only optic-flow information. Second, knowing that such extraction was indeed feasible, researchers have tried to identify any conditions under which such optic-flow information is actually used. We consider these two lines of investigation in turn.

Accuracy of Heading Judgments Based on Optic Flow

For modes of human locomotion such as walking, running, skiing, and driving, Cutting (1986, pp. 277–279) estimated the accuracy with which people needed to assess their own heading in order to avoid obstacles. For example, suppose a person who is 1.75 m tall and weighs 65 kg runs steadily at 5 m/s (approximately 11 mph). Assuming that the runner has normal reaction time, in order to swerve to avoid an obstacle such as a tree, the runner would have to judge his or her own heading to an accuracy of at least 1.6 deg visual angle. If the same person walked rather than ran, far less precise heading judgments would still afford a margin of safety. For downhill skiing, in which velocities may be nearly three times

that of running, the margin of safety narrows to 0.78 deg visual angle, which heightens skiing's potential risk.

How do such theoretical estimates square with what human observers can actually do? Empirical measurements of such judgments showed that with paths generated by pure translation across a ground plane, human observers achieve the performance level that Cutting stipulated (Warren, Blackwell, & Morris, 1988). Warren et al. created two-dimensional displays in which movements of display elements simulated an optic-flow field produced by an observer's movement. When viewing random dot displays that represent various directions of self-movement through the environment, observers can judge direction to an accuracy of about 1 deg visual angle (Warren et al., 1988). This level of visual precision is maintained whether the observer's gaze remains fixed or shifts with eye movements of the sort that observers might make while walking through a real environment. Furthermore, direction judgments are relatively robust in the face of visual noise added to the otherwise consistent motions of simulated flow fields (van den Berg, 1992).

Most experiments on the accuracy of heading judgments have used displays that simulate retinal consequences of simple, straight paths through the environment. In an important departure from this approach, Warren, Mestre, Blackwell, and Morris (1991) simulated self-motion on a curved path. After viewing random dot fields that simulated some curved path through the environment, observers were shown a distant target and had to judge whether the path they had seen would have taken them to the left or to the right of the target. Warren et al. measured heading thresholds for paths with varying radii of curvature and densities of dots in the flow field. Paths with typical curvature supported thresholds of 1.5 deg; performance was unchanged by even dramatic reductions in the number of random

elements in the display. This finding carries theoretical weight. Neural network-based explorations predicted that a pair of elements seen in two successive views would provide visual information sufficient to support perception of an observer's curved path (Warren, Blackwell et al., 1991). As a public service for drivers and downhill skiers, we note that accuracy of path judgments is severely degraded at small radii of curvatures (sharper turns).

Under many conditions, then, observers can judge their own paths quite accurately based on optic flow. However, examination of this ability has been limited to movement over single, simple paths. Does optic flow play a role when people attempt to navigate complex, multilegged paths? To answer this question, Kirschen, Kahana, Sekuler, and Burack (2000) asked people to navigate computer-generated synthetic environments with and without salient optic flow. Using the arrow keys on a computer keyboard to control their own simulated self-movement, Kirschen's participants made repeated trips over what had originally been a novel path. Trips grew faster as participants learned the environment's layout. Because these test environments were series of identically textured virtual corridors and intersections, participants needed to construct some mental representation of the environment in order to perform the task. By varying the rates at which the display was updated, the researchers created optic flow that was either smooth or choppy. The choppy condition created the impression of a series of separate still views of the environment. The availability of smooth optic flow promoted faster learning of complex paths, mainly by preventing disorientation and backtracking. In a second experiment, participants navigated within a virtual city-block environment, experiencing two different kinds of optic flow as they went. Smooth optic flow enhanced observers' ability to navigate accurately to

the remembered position of target objects. Kirschen et al. concluded that when other cues (e.g., distinctive landmarks) are not available, optic flow can be a significant aid to navigation.

Mere availability of reliable optic-flow information does not guarantee that all observers will be equally able to exploit such information. Here we consider two classes of observers for whom the quality of heading judgments is diminished.

Ball and Sekuler (1986) showed that healthy older people in their 70s and 80s had elevated direction discrimination thresholds. Although these measurements involved random dot motion in a front-parallel plane rather than heading-related judgments, the older observers' elevated thresholds might be a sign of some general age-related decline in motion perception, particularly perception of multi-element displays and tasks requiring heading judgments. Warren et al. (1988) measured heading thresholds for two groups of people, young (mean age about 20 years) and old (mean age of late 60s). Observers saw optical velocity fields that would be produced by observer translation or by observer movement along a curved path. After each display, which lasted about 4 s, a vertical line was presented, and observers had to judge whether the heading direction that they had seen would have taken them to the left or right of the line. With straight paths, young observers' heading thresholds averaged 1.1 deg visual angle, whereas older observers' heading thresholds were significantly higher, 1.9 deg visual angle. With curved paths, the corresponding threshold values averaged 1.4 and 2.9 deg visual angle. After ruling out ocular and other peripheral causes, Warren et al. suggested that these substantial age-related declines in heading acuity resulted from changes in high-level visual processing.

Patients with Alzheimer's disease, a progressive, degenerative disease of the brain,

often have difficulty finding their way around their surroundings, even when those surroundings are familiar. Two groups of researchers have connected this difficulty to subnormal processing of information contained in optic flow. If optic-flow information actually guides navigation, at least under some circumstances, then failure to process that information fully could produce spatial confusion and loss of one's bearings. Rizzo and Nawrot (1998) showed that patients with mild to moderate Alzheimer's disease have particular trouble extracting form or shape information from stimuli in which the form is defined by movement (shape from motion). Moreover, Tetewsky and Duffy (1999) showed that some patients with Alzheimer's disease are impaired in extracting directional information from optic-flow stimuli. Many of these same patients showed correspondingly poor performance on a test of spatial navigation (wayfinding) ability.

Is Optic Flow Normally Used to Guide Locomotion?

Observers' abilities to exploit the information in optic flow in order to judge heading does not guarantee that such ability is actually used to control locomotion. To see whether the information was used, Warren, Kay, Zosh, Duchon, & Sahuc (2001) allowed individuals to walk freely in a very large room while wearing a head-mounted display that afforded wide-field stereoscopic vision of computer-generated imagery. At the same time, head position was tracked, and head-position signals were used to update the computer imagery at 60 Hz. While viewing several different sorts of display images, observers attempted to walk as quickly as possible to a visible target such as vertical line or a doorway. Under normal viewing conditions outside the laboratory, walkers could base their locomotion on information other than the optic flow generated by their own movements. There-

fore, a walker could register the position of a seen target in egocentric coordinates and then walk toward that target's position, trying to remain centered on the target. Ordinarily, the optic flow generated by this egocentering strategy would be identical to the flow generated if an observer used the flow itself to control locomotion. Warren et al. broke this normal correlation by feeding participants optic-flow information that deviated systematically from what their movements alone would have generated. In a control condition, when no optic-flow information was provided, observers' paths indicated that they had walked in the egocentric direction of the target. Thus, they homed in on the target by keeping it centered with respect to their bodies. In other conditions, optic flow was introduced, with the unusual arrangement that the focus of expansion was offset from the walking direction (by 10 deg visual angle). As additional optic flow was introduced into the displays—by adding texture to floors and ceilings—observers' navigation behavior changed dramatically. Now, instead of walking toward the target as observers had been instructed to, they tended to follow the optic flow, which was intentionally misleading. It appears, then, that under normal conditions the visual system depends on both optic flow and egocentric localization, using the two sources of information in a complementary fashion. Warren et al. noted that when flow is reduced (e.g., on a grass lawn or at night), reliance on flow is also reduced, but that in environments that afford considerable optic flow (e.g., forested areas), locomotor behavior is likely to be dominated by flow.

Optic Flow Supports Collision Avoidance

When an observer is on a collision course with an object, the object generates a characteristic spatiotemporal expansion on the observer's retina. This fact holds equally well, of course,

for a moving observer and a stationary object, or vice versa. If the rate of movement is constant, the retinal angle subtended by the object grows nonlinearly in a nearly exponential fashion.

Animals as dissimilar as fiddler crabs, chicks, monkeys, and human infants all try to avoid looming patterns created artificially on television screens (Schiff, 1965). This is true even for newborn infants who have never before encountered a looming stimulus. Apparently, learning plays little role in this behavior.

The rate of retinal image expansion specifies the time to collision, that is, the moment at which a moving observer would reach the object. If at time t an observer D meters away from the object starts moving steadily toward the object, time to collision is given by travel distance divided by travel rate, D/R . Recognizing that solving for time to collision would require information about both D and R , Lee (1980) suggested that vision exploited another dynamic source of information about time to arrival, which would make it unnecessary to know either D or R .

Tau, the variable that Lee (1980) introduced, is the ratio between the current retinal image size and the rate of change in that image size. If the visual system computed a value approximating tau, time to collision would be given by tau's reciprocal. Note that this calculation's result is independent of object size.

The connection between imminent collision and the rate of expansion of retinal image size holds for any moving creature that has its eyes open—including birds that fly along and then dive at great speeds in order to catch a fish in the water below. Among the best studied of these diving birds is the gannet, a large web-footed seabird with a sharply pointed beak. Gannets fly along with their wings spread wide until just before their diving bodies would hit the water's surface, at which point

they tuck their wings tight to their sides. Timing is everything. If a gannet performs this maneuver too late, the impact with the water could be quite damaging; if a gannet folds its wings prematurely, its body will be buffeted by cross-winds that will alter the point of entry into the water. Although we have no wings that need folding, the human visual system carries out similarly complex computations. For example, information about the rate of expansion can be used to control the braking of an automobile (Lee, 1976), the split-second changes in gait needed when running across rough terrain (Warren, Young, & Lee, 1986), or the various movements and adjustments of the hand that are required for catching a ball (Savelsbergh, Whiting, & Bootsma, 1991). This coupling between optical expansion and action is not performed consciously. People succeed in these tasks despite being unaware—or being unable to articulate—what they are doing (Savelsbergh et al., 1991).

Although tau may be helpful in many circumstances in which people must recognize collision time, it cannot be the only effective cue to collision. In fact, tau would fail under a number of conditions (Tresilian, 1999). For example, if the approach rate is not constant, tau evaluated at any single moment fails to give the correct collision time. Gravity-induced acceleration also undermines tau's usefulness as a predictor of when a falling body will strike some surface. Additionally, with a very slow approach to an object, the rate of image expansion could become so small as to drop below threshold.

Tresilian (1999) discusses tau's limitations, and catalogs other cues that observers could and, in fact, do use. Human observers seem to be quite flexible in making use of available information to solve the collision problem. Thus, Schrater, Knill, and Simoncelli (2001) showed that observers can estimate expansion rates in the absence of optic-flow information by using only gradual

changes in the scale of random texture elements. In a simulated ball-hitting task, Smith, Flach, Dittman, and Stanard (2001) demonstrated that observers optimize performance by adjusting the relative weights given to cues such as the approaching object's angular subtense and rate of expansion.

It is both plausible and theoretically attractive to postulate that observers adjust cue weights to match task demands and to reflect the reliability and availability of various cues. This theoretical proposition, however, raises a series of theoretical questions about the control architecture that might be used to integrate task-specific processes (Hildreth, personal communication, May 2001). For example, do observers always generate the values of all potential information sources and then use an optimization strategy to select the most reliable? Or do observers actually generate only one or two preselected weights, based on the characteristics of the situation and task? Such questions must be asked and answered in order to clarify the real value of postulating observers's flexibility in choice of strategy.

Optic Flow Supports Perception of Object Structure

Kinetic Shape

In the laboratory, motion is a potent specifier of shape. This potency was demonstrated in studies by Regan (1989), who created displays in which alphanumeric characters were defined by clusters of dots moving in different directions. To illustrate, imagine a dense array of tiny dots, each of which moves. Now suppose that dots in a subset of those dots, which fall within the boundaries of a virtual shape, all move in the same direction, while dots outside the shape's boundaries move in a different direction. (It is important to realize that the region of the virtual shape itself is not

necessarily moving; only the dots defining that area move.) People readily see a figure defined by those common motion vectors, and they can judge with excellent accuracy the shape of that figure. Called "kinetic form perception," this ability is conserved in the face of substantial amounts of random motion noise.

The perception of biological motion provides another compelling example of vision's ability to recover object information from motion. When an animal's body moves, the body deforms; that is, various parts of the body move relative to one another. These characteristic relative movements are signatures of normal biological motion. In fact, when a human moves with stiff or locked body joints, reducing the normal movement of body parts relative to one another, the body's movement looks unnatural, artificial. Because normal biological motion involves deformation of the body, biological motion is classified as nonrigid motion. Although there are many nonbiological sources of nonrigid motion (e.g., the movement of a flag waving in the breeze), perception of human body movement has drawn the most interest and research.

In studies of biological motion, the activity and identity of an animate creature are extracted quickly and compellingly from merely a dozen or so "light points" placed strategically on the creature's body (Johansson, 1973). In animation sequences that represent the points' movements over time, no single point conveys information about the object or event being depicted. Individual points merely undergo translational or elliptical motions, or both. The lights promote perception best when they are placed on joints, the parts of the body whose movements are most diagnostic. Perception of a biological organism that is engaged in an activity requires global integration of motion signals over space and time. As a result, the perception of such animation sequences is literally the *creation* of

motion information (in the same sense that perception of an object in a random-point stereogram is the creation of binocular disparity information). Even a brief view of a point-light display allows an observer to identify the gender of the person in the display (e.g., Kozlowski & Cutting, 1977; Mather & Murdoch, 1994), the activity in which the person is engaged (Johansson, 1973), or the person's emotional state (e.g., Brownlow, Dixon, Egbert, & Radcliffe, 1997). Human infants as young as 3 months of age can perceive biological motion (e.g., Fox & McDaniel, 1982), as can adult cats (Blake, 1993). Perception of biological motion is remarkably robust in that observers can readily discriminate biological from nonbiological motion even when the points' contrast changes randomly over time or when the points are defined entirely by texture and not by luminance (V. Ahlström, Blake, & Ahlström, 1997).

The perception of biological motion may be mediated, at least in part, by unique motion mechanisms. First, information specifying biological motion can be summed over much longer temporal intervals than can information for simple translational motion (Neri, Morrone, & Burr, 1998). Second, damage to specific regions of the brain can impair perception of biological motion while leaving intact other forms of motion perception (Cowey & Vaina, 2000). Conversely, damage to other regions of the brain impairs perception of translational motion but has no influence on perception of biological motion (Vaina, Lemay, Bienfang, Choi, & Nakayama, 1990). Finally, functional neuroimaging (Grossman, Donnelly, Price, Morgan, Pickens, Neighbor, & Blake, 2000) has identified regions of the brain, located on the posterior STS, that are active during the viewing of biological motion, but not during the viewing of the same local motion vectors scrambled in space. These specialized regions are located anterior and superior to area MT+.

Kinetic Depth

In addition to object shape, motion information can also convey the three-dimensional spatial structure of surfaces. A single view of a stationary two-dimensional projection of a three-dimensional object affords little unambiguous depth information. When the object is set into motion, however, its projection can produce a clear impression of the object's depth and spatial structure. Wallach and O'Connell (1953) provided an early report of this phenomenon, which they dubbed the "kinetic depth effect." Today, the preferred term for the general class of phenomena is "structure-from-motion," which encompasses not only the emergence of depth from motion but also the generation of surfaces and other object-related properties. Specially constructed motion displays have been crucial to understanding the computational and neural bases of structure from motion. Figure 4.6 illustrates the construction of one such stimulus display. A computer is programmed to create a flat, two-dimensional projection

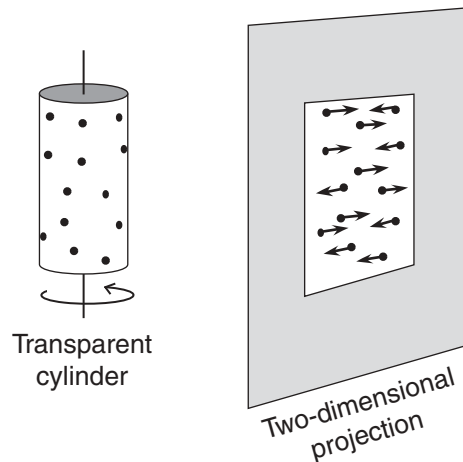


Figure 4.6 Two-dimensional projection (right) of transparent rotating cylinder (left).

NOTE: The dots on the cylinder's surface create intermingled left- and right-moving dots in the two-dimensional projection.

of a revolving, speckled, transparent, vertical cylinder. Viewing this two-dimensional projection, an observer sees intermingled rightward-moving and leftward-moving dots (arising from front and rear surfaces of the cylinder). Additionally, the speeds of individual dots will vary systematically across the display, and the fastest-moving elements will be projections of dots that lie closest to the left and right edges of the cylinder's projection. This two-dimensional projection typically produces a strong percept of structure from motion, giving rise to a bistable percept: a cylinder whose direction of rotation alternates between front leftward and front rightward (Andersen & Bradley, 1998).

In humans, the ability to exploit motion as the source of three-dimensional shape information seems to develop very early. Using a habituation technique, Arterberry and Yonas (2000) showed that infants as young as 8 weeks can perceive three-dimensional object shapes defined only by optic flow. This early access to structure from motion is fortunate because mechanisms that extract static-form information are relatively immature in early infancy.

Having seen the potential importance of shape from motion, one can ask how that information is actually extracted from the optic array. Originally, it was thought that three-dimensional structure in displays such as the one in Figure 4.6 resulted from a series of matches, over successive samples, of the spatial locations at which elements are located (Ullman, 1984). Such an algorithm, in which spatial positions were matched, ignored contributions from local motions, whose central role in structure from motion has been proven conclusively (Andersen & Bradley, 1998).

To explain the neural basis for structure from motion, Nawrot and Blake (1991b) devised a neural network incorporating interactions between stereopsis and direction-selective neurons (1991a). Because some

neurons in area MT are tuned not only for motion but also for stereo depth, Nawrot and Blake's model incorporated units tuned to combinations of disparity (e.g., near vs. far) and of direction of motion (e.g., left vs. right). The display shown in Figure 4.6 would activate two different types of units in a network of neurons: units sensitive to the conjunction of near disparity and rightward motion and units sensitive to far disparity and leftward motion. Mutual inhibition among units tuned to a given depth plane put them into an opponent relationship, and activation of one type of unit (e.g., near-depth leftward) tended to reduce responses in units signaling the opposite direction of motion (in this case, near-depth rightward). These within-plane interactions ensured that activity at a given depth plane was associated with only one direction of motion. In addition, units tuned to the same direction of motion in near- and far-depth planes also exerted mutual inhibition on one another. These between-plane interactions promoted segregation of different directions of motion into different depth planes. Together, these opponent arrangements keep the network from generating contradictory percepts within any local area, just as in the physical world any single, local region on the cylinder's surface cannot simultaneously move leftward and rightward.

Nawrot and Blake (1991b) assigned their units nonlinear stimulus-response activation functions. This nonlinearity, together with excitatory connections among similarly tuned units, allows structure from motion to build up over time, which is consistent with human observers' experiences with many such displays. For example, under many conditions the full structure of a display such as the cylinder in Figure 4.6 can take as long as a second or more to emerge fully. Similar cooperative interactions among like-tuned neural units have been implicated in other aspects of motion perception (Nawrot & Sekuler, 1990;

Williams, Phillips, & Sekuler, 1986). Finally, the model's combination of noise (moment-to-moment variability in response) and opponent organization caused it to reproduce another notable feature of human perception of structure from motion: a perceptual bistability produced by ambiguous displays such as the cylinder. Confirming this general idea, analogous bistability can be seen in the behavior of MT neurons in the brains of monkeys who view ambiguous two-dimensional displays such as the projection of the cylinder (Andersen & Bradley, 1998).

Nawrot and Blake's (1993) model makes some interesting predictions. First, because kinetic depth and stereoscopic depth are computed within the same neural network, the model predicts that it should be possible to create stimulus conditions in which the two forms of depth—kinetic and stereoscopic—will produce equivalent perceptual experiences. That prediction was confirmed in a series of experiments. In one experiment, observers viewed two successive animations depicting a rotating sphere. In one display, the impression of a three-dimensional sphere was created solely by kinetic depth; in the other display, retinal disparity was used to portray the sphere. For some disparities, these two displays were indistinguishable under forced-choice testing. A related experiment revealed that a weak sense of depth from retinal disparity could be reinforced or, alternatively, canceled by a strong kinetic-depth stimulus that itself contained no explicit disparity information. This finding, too, points to a common neural substrate for kinetic depth and dynamic stereopsis. A kinetic-depth stimulus's capacity to bias stereoscopic depth is comparable to the effect of direct, localized electrical stimulation of direction-selective MT neurons. In monkeys, stimulation of area MT has been shown to bias perceptual judgments of depth (DeAngelis, Cumming, & Newsome, 1998).

MOTION TRANSPARENCY

When an observer views a display in which two or more velocities are spatially intermingled, the percept can be one of transparency (two or more separate patterns moving through one another) or coherence (patterns cohering and moving in a single direction). Gibson, Gibson, Smith, and Flock (1959) reported that observers could detect two overlapping planes in a display in which the planes moved at different speeds. Subsequently, Andersen (1989) demonstrated that observers could accurately identify the presence of up to three planes in similar displays with a duration of 2 s. When duration is reduced to only 250 ms, observers can distinguish between a display comprising as many as five transparent sheets of dots moving in different directions from a display of dynamic random noise (Mulligan, 1992). Furthermore, with translatory movements the process of segregating a display into different planes is fast: With just a 60-ms exposure, observers can correctly identify a two-plane stimulus. However, if more complex motion patterns such as expansion/contraction and rotations are superimposed and presented for brief durations (85 ms followed by a random noise mask), observers cannot accurately identify the component motions (De Bruyn & Orban, 1993).

In transparent displays, the dots defining each separate plane usually move in phase, as an intact pattern in a given direction and speed. However, transparency can also be observed if individual dots in the display alternate between two different speeds (Bravo & Watamaniuk, 1995). In these cases, transparency is perceived, as evidenced by observers' abilities to judge accurately the speeds of individual component motions.

Although two spatially superimposed sets of dots moving in different directions can generate perceptual transparency, the two sets of

motion signals do not operate without mutual interactions. Specifically, the perceived directions of the two sets of dots appear to be further apart than they actually are, a phenomenon referred to as motion repulsion (e.g., Hiris & Blake, 1996; Marshak & Sekuler, 1979). If the directions of the superimposed sets of dots differ by less than approximately 90 deg, the perceived direction of each motion will be pushed away from the direction of the other motion. The magnitude of this repulsion effect depends on the speeds of the component motions and on the density of the moving elements (Dakin & Mareschal, 2000; see also Lindsey, 2001). In addition, Snowden (1990) and Verstraten, Fredericksen, van Wezel, Lankheet, and van de Grind (1996) showed that sensitivity to the direction of each motion plane decreases as the speeds of the two motion planes become more similar. Thus, although the percept of transparency shows that vision segregates component motions from one another, when the two motion signals are sufficiently similar, each can influence the perception of the other.

The percept of transparency requires a single local region to contain more than a single direction of motion. But what is the size of such transparency-producing regions? Qian, Andersen, and Adelson (1994) addressed this issue by generating direction-balanced displays in which dots moving in opposite directions (left and right) were either paired, so that a dot from each set was in close spatial proximity to the other, or unpaired. The observer's task was to judge the degree of transparency in the display. When the paths of the briefly presented dot pairs crossed or when they were separated vertically by 0.2 deg or less, the percept of transparency was abolished. In both cases in which transparency is abolished, the oppositely moving dots were close to one another. A similar lack of transparency is perceived if

two oppositely moving sine-wave gratings are superimposed.

Transparency can be restored to dot and grating displays if the components are sufficiently separated in depth, or if component gratings differ in spatial frequency by about two octaves.⁹ Curran and Braddick (2000) refined this work, showing that if paired dots moved in directions separated by just 60 deg to 120 deg, rather than in opposite directions, then the percept was that of coherent global flow in the direction of the dots' vector average. Presumably, paired directions differing by only 60 deg to 120 deg does not trigger the inhibition that would be generated had the directions opposed one another, that is, had they differed by 180 degrees. Similarly, Lindsey and Todd (1998) found that motion signals embedded in random noise were more easily detected when the component motions moved at right angles to one another, rather than in opposite directions. These data are consistent with the existence of a suppressive stage of motion processing in which oppositely tuned motion detectors inhibit each other locally. When the directions of spatially proximate motions are opposite one another, directional signals are perfectly balanced, and mutual, direction-selective inhibition results in no net perceived motion (Qian, Andersen, & Adelson, 1994). When spatially proximate signals differ by just 90 deg, the absence of directional inhibition enables observers to see the motion easily, as Lindsey and Todd found.

Neurophysiology provides further support for this hypothesis. Qian and Andersen (1994) recorded responses from V1 and MT neurons during presentation of paired or unpaired motion stimuli and found that V1 cells

⁹A difference of two octaves means that the spatial frequencies differ by a factor of four. With a difference this large, the two gratings will be initially registered by different spatial frequency tuned visual mechanisms (Graham, 1989).

responded equally well to both types of stimuli, but that MT cells responded better to stimuli in which local motions were unpaired. Snowden, Treue, Erickson, and Andersen (1991) reported data that were consistent with these results. But what about the brains of humans? Does the human motion complex (area MT+) behave as its nonhuman primate homologues do? Does area MT+ exhibit motion opponency? To answer this, Heeger, Boynton, Demb, Seidemann, and Newsome (1999) compared multiunit recordings from neurons in monkey cortex to the fMRI activation patterns generated in the human brain. A multiunit recording collects responses from local aggregates of neurons, rather than from individual neurons in isolation. This approach was meant to enhance comparability with fMRI measurements, which represent aggregated neural activity. Heeger et al. used equivalent stimuli for both measures of neural activity, and with both species. In humans as well as in monkeys, area V1 showed no evidence of motion opponency: Responses to paired and unpaired stimuli (dot patterns or gratings) were essentially the same. However, area MT in the monkey and its homologue in humans showed considerable motion opponency. In particular, the fMRI activation in area MT+ was far stronger with nonpaired dot stimuli than with dot patterns in which local, opposite motions were pitted against one another. Thus, area MT+ is a site at which direction opponency could initiate the assessment of transparency.

HOW THE VISUAL SYSTEM MEASURES MOTION: THREE PROBLEMS TO SOLVE

This section provides an overview of three major problems that vision must solve in order to provide observers with useful accounts of motion in the visual field.

Direction Selectivity/Reichardt Detectors

The first computational account of motion perception arose five decades ago, from the collaboration of Bernhard Hassenstein, a biologist, and Werner Reichardt, a physicist (Borst, 2000). Their product was a simple multiplicative correlation detector made up of two oppositely tuned subunits. To understand the detector's operation, imagine that a spotlight moves across the retina, successively stimulating different groups of adjacent photoreceptors one after another. To simplify, assume that the direction of the moving spot caused the spot to fall first on photoreceptor A and then, after some delay Δt , on photoreceptor B. As a result, the luminance signal elicited from A precedes the signal generated from B by Δt . This delay depends on two variables, the spatial separation between A and B, and the speed with which the spot moves. Now to the detector's circuitry: For one of the detector's subunits the luminance signal generated in photoreceptor A is multiplied by a delayed luminance signal from a second neighboring photoreceptor set, B. This basic operation is replicated in the detector's other subunit, but in mirror-symmetrical fashion: The two photoreceptors are switched, and the delay is now applied to the signal from the previously non-delayed photoreceptor. Because of the delays, a spot that reaches first A and then B generates a response that is larger in the second subunit than in the first; the same spot traveling at the same speed but in the opposite direction generates a response that is larger in the first subunit than in the second. In other words, the numerical difference between the two subunits' responses is directionally selective: Motion in one direction generates a positive difference, whereas motion in the opposite direction generates a negative difference.

The model's simple circuit guarantees that motion sensitivity will reflect a stimulus's temporal and spatial parameters, which is

certainly true of vision. In its first tests, the model was applied to insect vision to exploit as a behavioral index of motion perception the optomotor reflex of the beetle *Chlorophanus*. The model's success inspired a good deal of research, including work on higher animals. It also promoted the creation of other models that performed a similar computation using different circuitry (Sperling & Lu, 1998).

Although the Hassenstein-Reichardt motion circuit has many virtues, it also has one property that could be considered a flaw: It fails to distinguish between two classes of stimuli that are physically quite different from one another. In particular, the circuit would give equivalent responses to (a) a spot that moved smoothly with the proper velocity from the receptive fields of one subunit's receptors to the receptive fields of the other subunit's receptors and (b) a spot that was presented to one set of receptive fields, then extinguished, and, after a delay, presented to the other receptive fields. With proper delays between presentations of the spot, this latter sampled or stroboscopic motion stimulus would be indistinguishable from its smooth counterpart. Scaled up to an entire human visual system, this perceptual "error" becomes quite important because it allows the sampled images that comprise film and video sequences to mimic smooth motion. The result of such a sampling process is known as "apparent motion," a designation meant to contrast with smooth or "real" motion. The quality of apparent motion (i.e., how smooth the motion appears) varies with a number of parameters, particularly the rate at which the stimulus is sampled in both space and time domains. As the interval lengthens between successive frames of display, the sampling rate is said to decrease. Intuitively, as sampling rate increases—and successive frames come closer together in time—the appearance of the sampled stimulus approaches that of a smoothly-moving stimulus.

Watson, Ahumada, and Farrell (1986) developed a simple model that predicts whether any spatial and temporal sampling rate would produce the appearance of smooth motion. Their model defines a spatiotemporal range of each observer's window of visibility. The boundaries of this window, a region in joint spatial- and temporal-frequency space, define the spatial- and temporal-frequency limits of the observer's sensitivity to energy in the stimulus. When the stimulus is sampled in time, as for video or film or computer displays, the sampling process generates energy at temporal frequencies in addition to the fundamental frequency. A low sampling rate produces energy over a range of low temporal frequencies; a high sampling rate produces energy over a range of high temporal frequencies. As a result, the higher the sampling rate, the more likely it is that the resulting energy will fall outside the window of visibility, which renders them invisible and perceptually inconsequential. Therefore, two stimuli—one smoothly moving and the other representing sampled motion—will appear identical if their spectra within the window of visibility are identical; portions of their spectra that lie outside the window are irrelevant. Using two different strategies for sampling stimuli, Watson et al. confirmed the essential validity of their elegantly simple model.

Following Hassenstein and Reichardt, most studies of motion perception have examined responses to drifting modulations of luminance (or chromatic contrast). These stimuli, termed first-order stimuli or Fourier stimuli, would evoke responses in visual mechanisms that are responsive to spatiotemporal variations in luminance or chromatic contrast. Such stimuli correspond to a dominant species of spatiotemporal modulation that are encountered every day, but such stimuli do not exhaust the possibilities. Some stimuli, termed second-order or non-Fourier stimuli, would elude detection by such

mechanisms (Chubb & Sperling, 1988; Pantle, 1973). Nevertheless, perceptually, such stimuli elicit strong motion responses. It is worth emphasizing that second-order motion is not merely a creation of the laboratory. A well-camouflaged creature moving against a background with the same texture markings as the creature's own will generate second-order motion only. The same is true for the waving of tree branches when wind blows through a forest, or wheat stalks waving in a wheat field.

Many psychophysical studies comparing first- and second-order motion have demonstrated clear distinctions between the two. The distinction between the two classes of motion stimuli has gained increasing theoretical significance from reports that localized lesions of the brain can selectively impair either first- or second-order motion perception, while sparing the unaffected form (Vaina, Cowey, & Kennedy, 1999; Vaina, Grzywacz, LeMay, Bienfang, & Wolpaw, 1998).

The Correspondence Problem

Some of the computational prerequisites of motion perception reflect computational obstacles to perception more generally. To appreciate this point, consider the problem of motion correspondence. It has long been recognized that the proximal stimulus underspecifies the distal stimulus. In describing this fact, Helmholtz (1866) noted that at any instant the distribution of light on the retina (the proximal stimulus) is consistent with an indefinitely large combination of stimulus objects and patterns of object illumination (distal stimuli). To resolve, or at least reduce, the proximal stimulus's massive underspecification of the distal stimulus, the visual system exploits various sources of supplementary information, including constraints and regularities embodied in the physics of the natural world.

Although motion perception must overcome the underspecification that is common to all perception, as a spatiotemporal process, motion faces some additional, unique sources of underspecification. An early stage of motion extraction requires correspondence matching. Some local pattern—for example, a luminance perturbation centered on retinal coordinates x_0, y_0 —is detected at time t_0 and matched at later time, t_1 , to the pattern located at new coordinates, x_1, y_1 . As this description implies, motion depends on a match or correspondence in space and time. As Attneave (1974) pointed out, when a stimulus comprises more than one element that moves, identification of correspondences over time becomes a challenge.

Measurements of element positions in successive samples insufficiently determine the motion correspondences of the samples.¹⁰ Simple demonstrations of this point are shown in Figure 4.7. If there are n elements in each of two samples, then there are at least $n!$ sets of correspondences consistent with the samples. (This calculation assumes that one and only one element in the second sample is matched to each element in the first sample.) Dawson (1991) argued that to resolve this motion correspondence, the visual system exploits a trio of global spatiotemporal constraints that mimic the properties of motion in the natural world. (“Global” implies that the constraints are applied simultaneously to the entire field of dots, or to large portions of the field.) These constraints are known as the nearest neighbor principle (minimize the mean displacements between points matched

¹⁰To illustrate the correspondence problem, we have used examples in which stimuli are time-sampled at a relatively low rate. For historical reasons, when such stimuli generate the experience of motion, that motion is often designated as *apparent motion*. It is important to note that despite our limited choice of illustrative examples, the correspondence problem confronts any biological motion system.

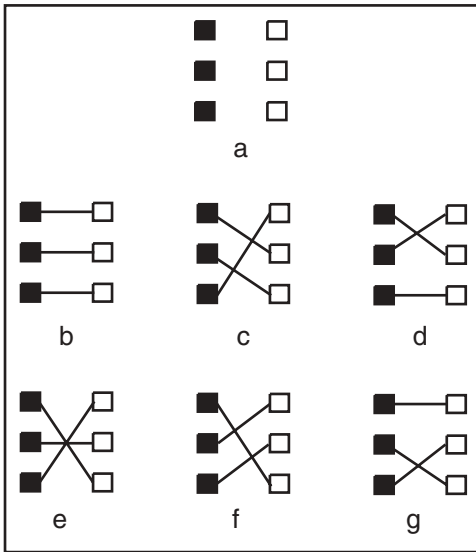


Figure 4.7 Illustration of motion's correspondence problem.

NOTE: In each panel, the three black squares represent items presented in the first frame of a cinematogram, and the three white squares represent items in the second frame. Panels illustrate various ways that items from the two frames could be matched.

SOURCE: After Dawson (1991).

between successive samples), the smoothness principle (because natural surfaces tend to vary smoothly, motion arising from the displacement of elements on such surfaces should be as smooth as possible, minimizing

abrupt changes in velocity among neighboring elements), and the element integrity principle (because surfaces do not tend to pop in and out of existence, elements on such surfaces should persist over time; i.e., one element should not split into two, and two elements should not fuse into one).

By emphasizing global motion matching, Dawson's (1991) model assumes that properties such as chromatic or shape similarities exert only a minor influence on motion correspondence. Although some empirical results have been taken as justifying that assumption, we believe that the preponderance of evidence leaves little doubt that motion correspondence is powerfully influenced by the similarity between stimuli. For example, A. B. Sekuler and Bennett (1996) examined motion correspondence generated by stimuli of differing calibrated discriminability. Manipulating relative phase—a crucial determinant of form perception—they assessed strength of correspondence produced by quartets of stimuli. Each quartet comprised four stimuli that were evenly spaced on a virtual circle. To emphasize the figural relationships among members of the quartet, we can designate the four stimuli as A, B, A, B.

Figure 4.8 illustrates the entire quartet rotated rigidly over 45 deg between successive display frames. Consider the four successive frames represented in that figure. If there

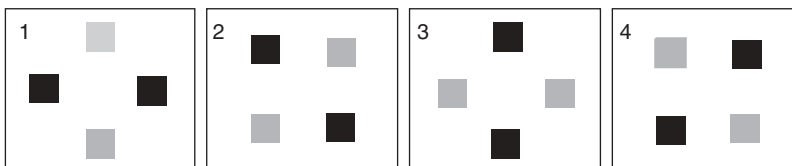


Figure 4.8 Four frames of a quartet display.

NOTE: In each frame, two tokens are black, and two are gray; the quartet of tokens rotates rigidly by 45 deg between successive frames. In the absence of color-based correspondence matching, the display's motion would be ambiguous, as likely to move clockwise as counterclockwise. However, color-based matching generates consistent motion in a clockwise direction, and the probability of seeing motion in the direction dictated by color matches increases with the perceptual difference between the two pairs of tokens.

were no color-based correspondence matching, the motion produced by the display would be ambiguous (i.e., as likely to move clockwise as counterclockwise). However, color-based matching would generate consistent motion in a clockwise direction. The elements in A. B. Sekuler and Bennett's (1996) quartets were compound sinusoidal gratings, each comprising a fundamental component and one harmonic component, at twice the frequency of the fundamental. A. B. Sekuler and Bennett manipulated the contrast and relative phase of the harmonic component in order to generate pairs of stimuli that varied in discriminability. When such stimuli were placed in quartet configuration (as in Figure 4.8), the probability of seeing motion in the direction dictated by figural matches varied with the perceptual difference between the two pairs of compound gratings. Tse, Cavanagh, and Nakayama (1998) described a novel class of displays in which figural parsing and matching are requisites for perception of motion. ("Parsing" refers to the segmentation, spatial isolation, and identification of separate stimulus elements.)

Before leaving the topic of motion correspondence, we should take special note of bistable motion sequences (i.e., stimuli in which the correspondence problem has two equally likely outcomes). An example of this unusual situation is illustrated in Figure 4.9, which shows two successive frames of animation sequence in which a pair of discs moves back and forth between two positions. Note that the upper disc in frame 1 could correspond either to the left-hand disc or to the right-hand disc in frame 2 (and likewise for the lower disc in frame 1). Because the two alternative motion paths are exactly equal in length, the motion system has no basis for deciding which pattern of motions is correct: Motion correspondence is entirely ambiguous. When stimuli like this are viewed for an extended period, people perceive both possible paths (Anstis & Ramachandran, 1987; Kramer &

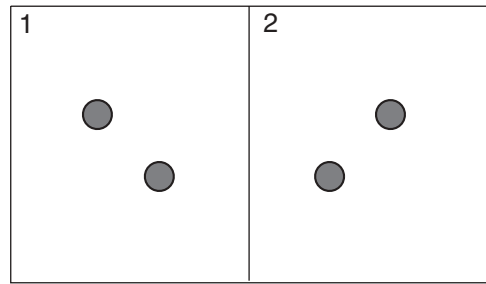


Figure 4.9 Two successive frames of a display that illustrates feature matching in the solution of a correspondence problem.

NOTE: The upper disc in frame 1 could correspond either to frame 2's left-hand disc or to its right-hand disc (and likewise for the lower disc in frame 1). Because the two alternative motion paths are equal in length, the motion system has no basis for deciding which pattern of motions is correct: motion correspondence is entirely ambiguous. When such stimuli are viewed for an extended period, both possible paths are seen in alternation.

Yantis, 1997; Pantle & Picciano, 1976; Ramachandran & Anstis, 1985), with each pattern of motion dominating for a few seconds and then giving way to the alternative pattern. Such ambiguous motion displays are useful tools for studying the stimulus factors that influence solutions to the correspondence problem (Francis & Kim, 1999; Yu, 2000). Multimodal stimuli, such as auditory signals, can influence the perception of bistable motion displays (Lewkowicz, in press; R. Sekuler, Sekuler, & Lau, 1997; Watanabe & Shimojo, 2001).

The Aperture Problem

As described earlier, local motion is extracted from the retinal image by neurons in area V1. The receptive fields of such neurons can be construed as apertures, spatially delimited windows within which neurons register the presence of motion in a given direction. If an extended moving edge or bar is seen within such an aperture, then regardless of the

direction in which the edge or bar actually moves, the neuron will respond as though the edge or bar were moving perpendicular to the orientation in the neuron's receptive field (Bradley, 2001). To take a specific instance, imagine that a smooth, featureless, vertically oriented bar moves obliquely (up and to the left) at a constant velocity. Any small receptive field positioned along the contour's length signals only the motion component that is perpendicular to the contour's orientation, in this case the leftward motion component. Because the contour extends beyond the boundaries of the small receptive field, the contour's upward motion component produces no information that changes with time (Pack & Born, 2001).

Because each directionally selective (DS) unit sees only what is happening within its own receptive field, the resulting signals from DS units are necessarily ambiguous. This ambiguity, now known as the aperture problem, was pointed out more than 60 years ago by Hans Wallach (Wuerger, Shapley, & Rubin, 1996). Figure 4.10 illustrates what Wallach had in mind. The circular area in the figure represents the receptive field of a DS neuron. Its preferred direction of movement is rightward. As the vertical edge of a large black line moves rightward at an appropriate speed through the receptive field, the neuron responds strongly (Panel A). However, this is not the only direction of movement that could evoke such a response. As long as the black line is large compared to the aperture (the receptive field), the same local spatiotemporal event—movement at the same velocity (meaning the same speed and direction)—could be generated by any number of other combinations of direction and speed, some of which are suggested in Panels B and C. This equivalence means that the neuron's response is inherently ambiguous. Because the neuron's view of the world is limited to the confines of its receptive field, the neuron responds exactly the same way to each of

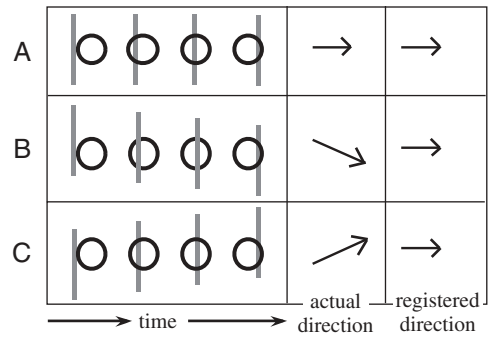


Figure 4.10 Illustration of the aperture problem: The ambiguity of directional information within a receptive field aperture.

NOTE: The circular area represents the receptive field of a directionally selective neuron tuned to rightward motion. As the vertical bar moves rightward through the receptive field, the neuron signals rightward motion (Panel A). However, movement of the same bar downward and to the right (Panel B), or movement upward to the right (Panel C) also generates rightward movement within the receptive field. The equivalence of these and other directions of actual movement renders the neuron's response ambiguous.

SOURCE: Modified from R. Sekuler and Blake (2001).

these different velocities of movement. As a prelude to explaining the visual system's strategy for resolving this ambiguity, consider one side effect of this ambiguity:

Movement seen within any single receptive field could have arisen from a variety of distinctly different visual events. This ambiguity opens the door to numerous illusions of perceived motion. With some of these, observers watch as a line or bar moves through an aperture whose shape strongly influences the perceived direction of movement. For example, suppose that an L-shaped aperture is cut in a piece of paper. Suppose also that a long oblique line (at 45 deg) behind the aperture moves steadily straight downward (Figure 4.11A). Initially, an observer sees an oblique line that moves downward. Then, once the line reaches the base of the

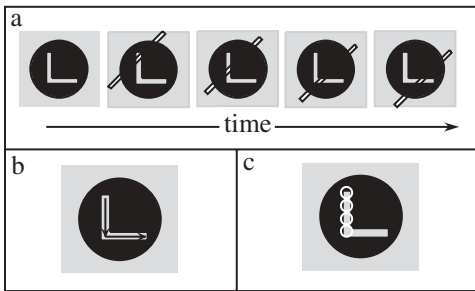


Figure 4.11 Wallach's demonstration of the influence of aperture shape on perceived motion.

NOTE: Panel A: Motion of an obliquely oriented line into, through, and then out of an L-shaped aperture. Panel B: The line initially appears to move vertically downward; then, when the line enters the aperture's horizontally oriented portion, its apparent direction abruptly changes to horizontal. Panel C: See text for an explanation.

SOURCE: Modified from R. Sekuler and Blake (2001).

L-shaped aperture, the movement abruptly changes (Figure 4.11B). Now the observer sees a rightward-moving oblique line. Wallach investigated this and several dozen related aperture illusions (Wuerger et al., 1996). To appreciate the basic elements of his approach, return to the L-shaped aperture.

One can approximate the L-shaped aperture's upright portion by a set of colinear circular receptive fields (Figure 4.11C). An oblique, downward-moving line would traverse each of these fields, one after another. However, this pattern of stimulation underspecifies the distal stimulus; in fact, the pattern of stimulation could have arisen from any number of distal stimuli. For example, it could have been produced by several different but similarly oriented lines, each of which traverses just one receptive field and then disappears, just as the next line appears at the top of the next receptive field and begins its own descent. Or, the same pattern of stimulation across all the receptive fields could have resulted, as it did in Wallach's

demonstration, from a single line that moved from top to bottom, entering and then exiting one receptive field after another. Given the limited information available to it, how does the visual system select the scenario that most likely was responsible for that information? In the spirit of Gestalt psychology, Wallach proposed that the single perceptual choice made in such multiple-choice situations tends to be the simplest global motion. In this case, an observer sees a single steadily moving line rather than a series of different lines in succession. An alternative view might portray the single perceptual outcome as the product of a Bayesian perceptual inference (Knill, Kersten, & Yuille, 1996). Choosing between these alternative accounts requires additional, carefully designed empirical measurements.

Perceived motion, then, is not determined solely by local responses to stimulus velocity that are generated within separate restricted regions of the field. Instead, local measurements of velocity are integrated at some place in the visual system at which the local velocity-related signals from area V1 are collected and combined. Such a combination of signals is the nervous system's standard operating procedure for resolving neural ambiguity in the signals of individual neurons. When the response of one neuron is ambiguous, the nervous system can diminish the ambiguity by aggregating outputs from a number of differently tuned neurons. For visual motion, the nervous system reduces ambiguity about individual, local, spatiotemporal events by channeling outputs from the first stage of direction processing to its second stage of neural processing in area MT.

Some neurons in area MT receive input from V1 neurons with different preferred directions of motion. As a result, the directional selectivity of these MT neurons differs qualitatively from that of their predecessors in area V1. Furthermore, these differences enhance

the importance of area MT's contribution to the perception of motion. To see this, return to Wallach's demonstration with two overlaid, moving gratings. When analogous two-component grating displays are imaged within the receptive fields of V1 neurons, the neurons tend to respond to the separate components. Some of Wallach's psychophysical observations foreshadowed these physiological results. He showed observers patterns composed of two different line gratings such as those shown Figures 4.12A and 4.12B. When the two are overlaid, as in Figure 4.12B, they generate a series of diamond-shaped structures. When the bars of the two gratings move downward at the same rate, the display's appearance fluctuates between (a) a field of diamonds that moves downward (Figure 4.12C) and (b) two line gratings that move at different

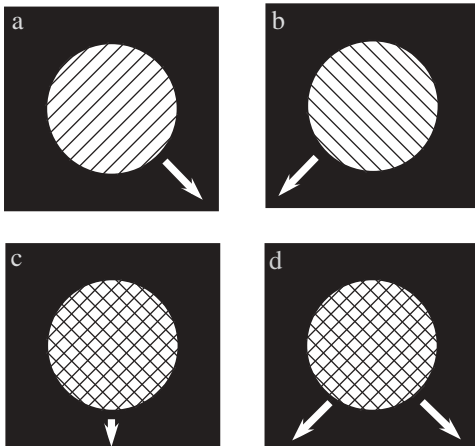


Figure 4.12 Superimposition of two diagonal, moving gratings (A and B) produces a diamond pattern whose motion is bistable.

NOTE: When either moving grating is presented alone, it appears to move in a consistent direction, which is indicated by the arrows in A and B. When the gratings are superimposed, they cohere to form a single downward-moving pattern (Panel C), or they appear to slide over one another, in two different superimposed directions.

SOURCE: Demonstration devised by Wallach. Diagram modified from R. Sekuler and Blake (2001).

velocities, sliding over each other in the process (Figure 4.12D). As Wallach found, the relative potency of the two alternative perceptual outcomes varies with a number of factors, including the angle between the two line gratings. This bistability is reminiscent of Rubin's vase/face illusion and of various phenomena of binocular rivalry (see R. Sekuler & Blake, 2001).

This perceptual bistability points to something quite important about motion perception. In order to parse the display into two gratings that move in different directions, the nervous system requires mechanisms that separate the different directions within each local region. However, to produce the alternative outcome—the moving diamond—the nervous system needs a second mechanism that collects dissimilar directional signals from regions across the display and binds those signals into coherent perceptual wholes rather than independent, isolated elements. This may sound challenging, but it is utterly necessary. In the example shown in Figure 4.12, these directions would be obliquely downward to the left and to the right. When the same displays are presented in the receptive fields of MT neurons, however, many of those cells respond to the motion not of the components, but of the overall moving pattern (Movshon, Adelson, Gizzi, & Newsome, 1986). In the case illustrated in Figure 4.12, this would be coherent motion directly downward. It is thought, then, that important aspects of motion perception arise from two stages of processing: one stage in which local motion vectors are extracted, and a second stage in which those vectors are sorted into object-related combinations. As Braddick put it, “[W]e do not live in a world of independent fragments, but of objects and surfaces that move coherently” (1993, p. 263). Vision needs some way to combine velocity signals that belong to the same moving object. It also needs to separate velocity signals that do not belong together,

that is, signals that arise from different objects (Snowden & Verstraten, 1999). Obviously, the characteristics of the world mandate precisely the sort of complex behavior that Wallach demonstrated.

Several computational strategies could be exploited in order to resolve the ambiguity represented by the aperture problem. Fennema and Thompson (1979) were the first to observe that the ambiguity could be overcome by combining two or more ambiguous measurements of local motion. Movshon et al. (1986) demonstrated that some neurons in area MT seem to perform precisely such a disambiguating computation, a computation that produces what is known as an intersection of constraints (Adelson & Movshon, 1982).

Pack and Born (2001) demonstrated a dynamic form of disambiguation in macaque MT neurons. As expected from the influence of the aperture problem, MT neurons initially responded primarily to the component of motion perpendicular to the orientation of a moving contour. Then, over approximately 60 ms, the neurons' responses shifted steadily. At the end of this dynamic process, neurons' responses began to signal the actual direction of the stimulus, no matter what the stimulus's orientation. This shift in neural activity had a striking correlate in the monkeys' oculomotor behavior, in smooth pursuit eye movements. The initial velocity of pursuit eye movements deviates in a direction perpendicular to local contour orientation, suggesting that the earliest neural responses influence the oculomotor behavior. These results suggest that the primate visual system derives an initial estimate of motion direction by integrating ambiguous and unambiguous local-motion signals over a fairly large spatial region and then refines this estimate over time. Lorenceau, Shiffrar, Wells, and Castet (1993) demonstrated an analogous result with human observers: The perceived direction of a field of moving bars is initially perpendicular to the

bars' orientation but shifts slowly toward the actual direction of movement.

Geisler (1999) called attention to yet another avenue to the disambiguation of motion signals. With a stimulus that moves relatively rapidly, the visual system's temporal integration produces an oriented *virtual* contour, which Geisler labeled a visual streak. (It is important to appreciate the virtual character of such streaks; they should not be confused with the actual streaks, or trails, sometimes generated as a wake when a bright target moves rapidly across the display of a cathode ray tube.) The orientation selectivity of neurons in area V1 means that motion streaks, which accurately reflect the direction of contour motion, could generate reliable orientation signals that can help disambiguate direction of motion (see also Jancke, 2000). Geisler buttressed his ingenious hypothesis with measurements of motion thresholds with simultaneous orientation masking and after orientation adaptation.

MOTION AFTEREFFECTS

When one stares at motion in one direction for some period of time and then gazes at a stationary scene, the static scene appears to move in the direction opposite to the previously viewed motion. Although prolonged exposure to motion has other consequences—such as direction-selective threshold changes and alterations in perceived velocity—illusory post-exposure motion defines what is known as the motion aftereffect (MAE).¹¹ Reports of this visual phenomenon can be traced back to Aristotle (about 330 B.C.) and Titus Lucretius Carus in about 56 B.C. (Wade &

¹¹Even very brief exposures to motion can generate substantial consequences, such as twofold, directionally selective decreases in sensitivity or clear alterations in perceived direction (Pantle, Gallogly, & Piehler, 2000).

Verstraten, 1998). The best-known early description of the phenomenon was given by Addams (1834), whose observation of the effect at Scotland's Falls of Foyer gave the phenomenon its common name, the waterfall illusion. Wade and Verstraten (1998) provided an excellent historical treatment of MAE, which is a widely used tool for studying motion processing more generally. In fact, the explosive growth in the literature on MAE, as documented by Mather, Verstraten, and Anstis (1998, p. viii) parallels the growth in published works on many aspects of visual motion.

The conditions under which MAE occurs were extensively studied by Wohlgenuth (1911). The strength of MAE can be assessed by any of a number of measures, including apparent speed, apparent direction, and duration (Pantle, 1998). Using MAE duration as an index of strength, Wohlgenuth found that maintaining fixation during the adaptation period increased the effect and that adapting one eye would produce an aftereffect in the other, an example of interocular transfer. This surprising finding was initially reported by Dvorak (1870) and has been replicated recently by others (e.g., Raymond, 1993; Steiner, Blake, & Rose, 1994; Symons, Pearson, & Timney, 1996; Wade, Swanston, & De Weert, 1993). The interocular effects are usually only half as strong as the monocular effects.

Many motion studies generated adaptation with drifting sinusoidal grating, whose effect was measured with a stationary test grating. Not unexpectedly, the MAE was tuned to spatial frequency: The strongest effect occurred when adapting both the grating and the stationary test grating had the same spatial frequency (Bex, Verstraten, & Mareschal, 1996; Cameron, Baker, & Boulton, 1992; Thompson, 1998). The effect also showed temporal frequency tuning; the strongest effect was reported at a temporal frequency of

5 Hz, regardless of spatial frequency (Pantle, 1974).

Although the aftereffect is evoked usually with a stationary test stimulus, more recent experiments have used dynamic RDCs as test stimuli (e.g., Blake & Hiris, 1993; Ledgeway, 1994). Using such test stimuli, aftereffect strength can be measured by having a proportion of dots in the RDC move in the adapted direction to null the illusory motion. Moreover, adapting to non-Fourier motion does not produce an aftereffect with static tests (McCarthy, 1993; Nishida, Ashida, & Sato, 1994; von Grünau, 1986), but an aftereffect is observed when the test stimulus is dynamic, such as a pattern of flickering elements (Ledgeway, 1994; McCarthy, 1993; Nishida & Sato, 1995). Some investigators feel that dynamic, rather than static, test patterns provide the most accurate reflection of the properties of motion mechanisms (Hiris & Blake, 1992).

The MAE ordinarily lasts for a relatively brief time following adaptation, typically decaying after about 1 s to 15 s. Although the passage of time strongly influences the decay of the aftereffect, other factors also play a role. In fact, certain conditions of test viewing can freeze the aftereffect's normal decay, causing the aftereffect to be stored (Spigel, 1960, 1962a, 1962b, 1964). Immediately after adaptation, if one closes one's eyes for a period that exceeds the MAE's expected duration, then the MAE will still be seen when the eyes are reopened. In other words, closing the eyes slows the MAE's normal decay. This phenomenon is often described as an example of *aftereffect storage*. Such storage has some interesting characteristics that have changed researchers' views of the MAE. For example, suppose that after adaptation the MAE is tested with a dynamic field (randomly moving dots). If the MAE is allowed to run its course with this dynamic test field and if a static test field is then presented, a MAE will be seen on

that field. Most surprising, the duration of the MAE on the static field will be little affected by the intervening dynamic MAE. Reversing the order of the two test fields (i.e., the static MAE followed by the dynamic MAE), the duration of the dynamic MAE is affected by the intervening static MAE (Verstraten et al., 1996). This relative independence of the static and dynamic MAEs, and other divergences between these two types of test fields, has encouraged the idea that adaptation can occur in at least two distinct regions of the brain. Specifically, Nishida et al. (1994) suggested that the static MAE is caused by adaptation in the primary motion detectors, whereas the dynamic MAE reflects adaptation in a higher cortical area, such as area MT.

Early modern accounts of the MAE assigned a central role to the fatiguing of cells during adaptation. These accounts exploited two key ideas: first, that neurons in the motion system fire spontaneously in the absence of motion, and second, that perceived direction of motion reflects the relative firing rates of neurons tuned to opposite directions. Suppose that the spontaneous activity of fatigued cells is significantly reduced for a brief time after adaptation. Therefore, the presentation of a stationary stimulus generates an imbalance in the spontaneous firing of the motion cells, and the nonadapted cells have a proportionately higher rate. According to this hypothesis, the brain takes this imbalance as signaling the presence of actual motion in a direction opposite to the earlier adapting direction (Barlow & Hill, 1963; R. Sekuler & Ganz, 1963; Sutherland, 1961). Such illusory motion is, of course, what people perceive. This model was labeled the ratio model because it held that perceived direction was controlled by the ratio of responses among motion cells that are tuned to different directions of motion. A somewhat modified version of this theory, dubbed the distribution shift model (Mather, 1980), recognized that adaptation would

affect a range of directionally tuned mechanisms, not just the one mechanism that was most sensitive to the adapting direction. The result would be a more widespread change in postadaptation spontaneous activity.

By incorporating various forms of inhibition, recent theories of the mechanisms of the MAE depart from earlier emphases on fatigue. This new emphasis reflects in part a recognition of the central role that inhibition plays in the cortex and, therefore, in visual computations. For example, Barlow (1990) proposed that the MAE results from a buildup of mutual inhibition among populations of motion-sensitive neurons during adaptation.¹² This mutual inhibition remains for some time after the adapting stimulus is removed. As a result, the pattern of responses among the motion cells is modified such that a neutral (stationary) stimulus is perceived as moving in the opposite direction. Because this inhibitory buildup could occur at any site where motion-sensitive cells are found, adaptation can occur at one or more sites in the motion system. Nishida and Sato's (1995) MAE results, mentioned earlier, are consistent with this idea.

Motion aftereffects can also be produced by stimuli comprising two superimposed directions of motion. Here, the resulting aftereffect is opposite the vector sum of the two adapting directions (Riggs & Day, 1980; Verstraten, Fredericksen, & van de Grind, 1994). Thus, for example, simultaneous adaptation to leftward motion and to upward motion subsequently causes a stationary test figure to appear to drift down and to the right (the vector sum of the downward component and the rightward component). When the two adapting components are unequal in strength

¹²For Barlow (1990), the MAE exemplified a general principle of neural operation. In his view, the mutual inhibition, to which he ascribes MAE, reduces redundancy in the firing of different sets of neurons, thereby minimizing the total activity at any site in the visual system.

(e.g., one component is of higher contrast than is the other), the aftereffect direction shifts toward the stronger component, and the size of the shift tracks the inequality between stimulus components.

MEMORY AND LEARNING FOR MOTION

Vision's essential purpose is to guide behavior, and that purpose is served best when vision's current products can be compared to stored representations of vision's earlier products. Such comparisons, or recognitions, enable animals to prepare situation-appropriate behaviors before they are necessary. Although much of the research on human memory has focused on memory for symbolic or verbal material, long before words came on the evolutionary stage, animals had a crucial need to remember and recognize scenes, objects, and events that they had encountered earlier. Although motion is certainly among the visual attributes that are worth remembering, relatively little research has been done on memory for motion.

Magnussen and Greenlee (1992) examined observers' short-term memory for stimulus velocity. Using drifting luminance gratings, they measured the difference threshold for velocity, ΔV . They explored the retention of velocity information in memory by varying the interstimulus intervals (ISI) separating the first (reference) stimulus and the second (test) stimulus. Weber fractions ($\Delta V/V$) proved to be independent of ISIs ranging from 1 s to 30 s. This invariance showed that memory for velocity is quite robust over delays of up to 30 s.

Blake, Cepeda, and Hiris (1997) explored memory for direction of movement by using RDCs with 100% coherence. After a 1-s presentation of an RDC, an observer used a computer mouse to indicate the direction in

which motion had been seen. The mean absolute value of observers' errors was about 5 deg (Blake, Cepeda, & Hiris, 1997). This level of performance is remarkably robust when pre-response delays force the perceived direction to be stored and then retrieved from memory. For example, performance is unchanged when the subject's response is delayed by 8 s. The memory on which responses were based is unlikely to be of an iconic nature; performance was unimpaired by random visual noise interposed between the RDC and the report of the remembered direction. Nor did memory depend on stored information from eye movement, such as observers might make while viewing the RDC: Performance was unaffected when observers executed random tracking-eye movements before making their judgments. Although memory for RDC direction was preserved over short intervals, such memory was dramatically undermined when Blake et al.'s observers saw not just one direction but a succession of different directions on each trial. Performance fell off substantially as the number of seen directions grew. For example, average error climbed from 5 deg with just one presentation to 25 deg to 30 deg when observers saw and tried to remember seven different directions of motion.

Pasternak and colleagues have studied the role of area MT in remembering the direction of visual motion (Bisley & Pasternak, 2000; Bisley et al., 2001). They trained monkeys to compare the directions of motion portrayed in two successively presented animation sequences, the "sample" and the "test." Task difficulty was manipulated by varying the coherence of these random-dot motion displays and the delay interval between sample and test. During the delay period—while the monkey was trying to remember the sample direction that it had seen—small, brief electrical pulses were delivered directly to clusters of neurons in area MT. This electrical stimulation, which artificially activated the recipient neurons,

influenced the monkey's subsequent judgment about the test direction (Bisley, Zaksas, & Pasternak, 2001). This result supports the notion that area MT is involved in the short-term retention and retrieval of information about the direction of visual motion. This conclusion receives further support from the same researchers' studies of the effects of unilateral lesions to motion centers of the monkey cortex (Bisley & Pasternak, 2000).

As mentioned in the introduction to this section, visual memory is an important guide for behavior. Memory of what people have seen allows us to prepare situation-appropriate behaviors and to execute them in a timely fashion. For visual movement, preparation of appropriate behavior requires recognition that some motion that is being experienced at a given time has in fact been seen before. Chun and Jiang (1999) showed that with repeated exposure to particular complex movement sequences, subsequent recognition of those sequences remains at the implicit level. In their experiment, observers searched for a single rotated-T target embedded in a field of L-shaped distractors. An animation sequence made all the search items—target as well as distractors—move randomly over the display screen; each item's random trajectory was independent of the trajectory of the other items. Because all the search items started the sequence as crosses, and only slowly morphed into their final form—a rotated-T or L distractors—observers had to monitor the entire set of randomly moving items. Unbeknownst to observers, some of the random sequences were repeated during the 72 experimental trials. Search time improved for all sequences, repeated as well as nonrepeated, but the improvement was dramatically stronger with repeated sequences. Because explicit recognition accuracy was no better than chance, Chun and Jiang applied the label “implicit” to the perceptual learning that they observed. This result supports the notions that

subjects can pick up and encode dynamic regularities or invariances and that they can do so without explicitly recognizing those repeating features.

KNOWLEDGE, ATTENTION, AND MOTION PERCEPTION

Attention takes many forms, all of which promote preferential processing of stimuli or stimulus attributes that are relevant to a particular task and inhibit processing of task-irrelevant stimuli or stimulus attributes (Chap. 6, this volume; Raymond, 2000). The selectivity that is represented by attention modulates the behavioral impact of any moving stimulus—up or down—in accord with an observer's task and goals. Performance on any task, whether in the laboratory or as part of everyday activity, implicitly reflects this modulation, which ordinarily operates unnoticed in the background. In this section, we consider a sample of experiments designed especially to highlight selectivity.

Tracking Multiple Objects

William James distinguished among forms of attention, noting that whereas people can attend to sensory stimuli (e.g., particular locations or objects), they can attend also to “ideal or represented objects” (1890, p. 393). In other words, James recognized that people could attend either to a thing that was physically present or to an object that existed only in the mind, which today might be called a virtual object. Attention's ability to influence virtual moving objects is demonstrated by results from a procedure devised by Pylyshyn and Storm (1988). The procedure measures the ability to keep track, over time, of multiple, spatially dispersed, independently moving targets. The task can be likened to watching some crows feeding in a field, and then,

Phase of Trial

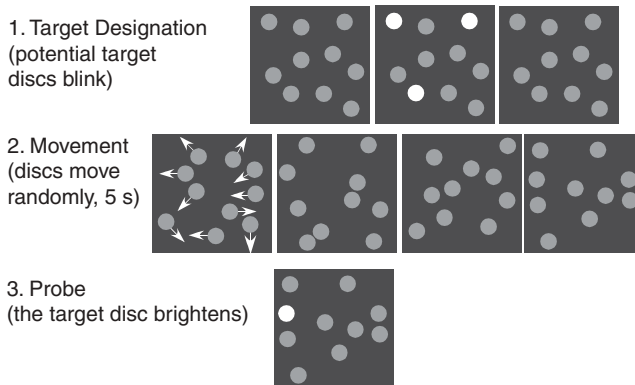


Figure 4.13 Typical trial structure for multiple-target tracking experiment.

NOTE: During trial's initial phase (target designation) several discs are singled out by a momentary brightening. During the second phase (movement) all discs undergo a series of random movements. In phase 3 (probe) a single disc is brightened, and the observer must judge whether that disc was among the ones that had been identified as potential targets during the trial's initial phase.

SOURCE: Modified from R. Sekuler and Blake (2001).

when the crows fly off in different directions, keeping track of each and every crow.

In a typical experiment on multiple-object tracking, a trial consists of three phases, called *target designation*, *movement*, and *probe*. Figure 4.13 illustrates each of the three phases. Target designation begins with the presentation of 10 targets, such as discs, scattered about on a computer display. Then three, four, or five of the 10 discs, chosen randomly, blink several times. This informs the observer of the discs that will be targets for that trial. In the movement phase, all 10 discs move about smoothly on the screen in various directions, each changing course unpredictably. After several seconds of movement, the trial's probe phase begins. One of the 10 discs is highlighted, and the observer must report whether that one probe item had or had not been one of the targets designated during the designation phase, several seconds before. Performance, summarized as the proportion of correct responses, is most accurate when people have to keep track of fewer targets (e.g., 3 instead of 4 or 5). This is consistent with earlier find-

ings that attention loses potency for any one item when additional items must also be attended to.

Yantis (1992) examined the influence of perceptual grouping on multiple-object tracking. In one experiment, for example, targets either were chosen at random or were chosen to lie at the vertices of virtual simple geometric figures, such as diamonds. At the outset of the experiment, performance was much superior when the target to be recognized had started out as part of a nice geometric perceptual group (during the target designation phase of a trial). However observers quickly learned to impose virtual groupings on elements that had not been part of ready-made, regular geometrical groupings. This erased the early advantage found with ready-made groupings.

Unless grouping is maintained during the movement phase, grouping at the start of a trial is no help at trial's end (the probe phase). By varying the targets' movements during the movement phase of a trial, Yantis controlled the likelihood that any existing grouping would be maintained. In one condition,

targets moved about randomly, which allowed one or more targets occasionally to cross over an opposite edge of the virtual polygon. This crisscrossing destroyed the original grouping, undermining the coherence of the virtual polygon and causing elements to lose identity as designated targets in that virtual polygon. In another condition, movements of targets were constrained, ensuring that none ever crossed over an opposite edge of the virtual polygon. Here, movements of individual targets produced moment-to-moment fluctuations in the shape of a virtual figure that would be created by connecting those targets. However, not one of these fluctuations was drastic enough to destroy the convexity of the virtual polygon. Performance was distinctly better when the virtual polygon was preserved. This suggests that observers' attention creates (in the target designation phase) and maintains (in the movement phase) an updatable virtual object that is used (in the probe phase) to determine whether the probed target was in the object.

To track multiple *moving* objects, the brain exploits neural circuits that are ordinarily dedicated to a different purpose, namely, shifting attention from one location in space to another. Culham et al. (1998) used fMRI to identify the brain circuits that participated in multiple-object tracking. Their results provide a clear picture of how the brain manages this difficult task. Attentive tracking of multiple, independently moving objects is mediated by a network of areas that includes parietal and frontal regions—known to be responsible for shifts of attention between locations and for eye movements—as well as area MT and related regions, which, as noted earlier, are central regions for processing motion information.

Uncertainty and Motion Detection

When it comes to detecting weak motion signals that are embedded in noise, it helps

greatly to know in advance in which direction the signal dots are moving: uncertainty about direction of motion impairs detection performance. In one study, Ball and Sekuler (1981) determined the ease with which people detected very dim dots moving across a computer display. From trial to trial, the direction of the dots' motion changed unpredictably. In addition, during half the trials, no dots at all were presented; the viewer saw only a blank screen. The dots were made dim enough that a viewer had great difficulty telling whether or not any dots were present. Ball and Sekuler measured the intensity threshold for detecting the dots under various conditions. Thresholds were initially determined simply by randomizing from trial to trial the direction in which the dots moved. Thresholds were then measured with an explicit cue that reduced the viewer's uncertainty about direction of motion. This directional cue was a short line flashed very briefly at different times relative to the presentation of the dots. The orientation of the line indicated the direction in which the dots, if present at all, might move (recall that no dots were presented on half of the trials).

Ball and Sekuler (1981) made several noteworthy discoveries. First, when the cue specified the direction of the dots' motion precisely, the dots were easier to see; that is, the intensity threshold was low. Second, the cue was not helpful unless it preceded the dots by about 500 ms, indicating that selective attention required some time to operate. Third, if the cue's orientation did not match the dots' direction precisely, but only approximated it, the cue could still lower the detection threshold, but not as much as when it was precisely accurate. Generally, the greater the discrepancy between the cue's orientation and the direction of the dots' motion, the more difficult it was to see the moving dots. In the extreme, a cue that misdirected the observer's expectation by 180 deg was worse than no cue at all: Detection fell below a no-cue baseline.

How do directional cues or certainty about direction exert the effect that they do? Cues or prior knowledge are not part of the stimulus, but they certainly do affect the response evoked by the stimulus. Obviously, some information extracted from the cue must be recoded into a format capable of influencing subsequent processing of the test stimulus. After this recoding process, the nonmoving cue then seems able to boost selectively responses in particular sets of directionally selective neurons.

Shulman et al. (1999) extended Ball and Sekuler's (1981) study by measuring brain activity while people performed the cued-motion detection task. As before, the stationary cue, presented prior to the moving target, specified the direction of motion that people would see. As revealed by fMRI signals, the nonmoving cue activated brain areas that included area MT, as well as adjacent regions that normally respond to motion. Also, some areas of parietal lobe that are not normally responsive to motion were activated. Together, these motion-sensitive and motion-insensitive areas constitute a neural circuit that encodes and maintains the cue during the interval between the cue and the onset of motion.

Presumably, prior information about the direction of motion temporarily boosts the signals of MT neurons that are particularly responsive to that direction of motion (Treue & Maunsell, 1999; Treue & Trujillo, 1999). This internally generated boost response is equivalent to what happens when the responses of particular directionally selective neurons are strengthened, either by the presentation of a strong visual stimulus or by direct electrical stimulation, as in the study by Salzman et al. (1992).

A. B. Sekuler, Sekuler, and Sekuler (1990) used direction uncertainty to explore detection of changes in direction of movement. *Direction uncertainty* refers to an observer's prior knowledge of stimulus direction; as de-

scribed earlier, uncertainty diminishes the detectability of motion, as indexed by elevated thresholds or lengthened reaction times. In this study, observers had to respond as quickly as possible to a constant relative change in stimulus direction: 30 deg clockwise. The prechange direction either was fixed within a block of trials (certainty condition) or was completely random (maximum uncertainty). Generally, responses to change in the certainty condition were considerably faster than in conditions of uncertainty. However, if the prechange motion lasted 500 ms or longer, observers' reaction times to change were no longer affected by uncertainty about initial direction. However, for shorter initial durations, reaction time increased with increased uncertainty (i.e., increased in the range of possible initial directions). A. B. Sekuler et al. proposed that the visual system requires approximately 500 ms to normalize the initial direction of motion in order to be able to detect the direction *change* by essentially converting the nominal task to one of detecting motion *onset*.

Alais and Blake (1999) used the MAE to probe the influence of attention on motion perception. As mentioned earlier, when the adapting stimulus comprises two directional components, the direction of the MAE is usually the vector sum of the two components; but when the components are unequal in strength, the resulting MAE tracks that inequality. By varying the relative contrasts of the two component adapting motions, Alais and Blake were able to manipulate how much attention an observer had to pay to one of the components. In their experiments, observers viewed a computer display consisting of two superimposed fields of moving dots. In one group, all dots moved coherently in a single direction, shown as "upward" in Figure 4.14. Dots in the other group moved in random directions most of the time, producing no net directional drift. Occasionally, a subset of the random dots joined forces to move in the same

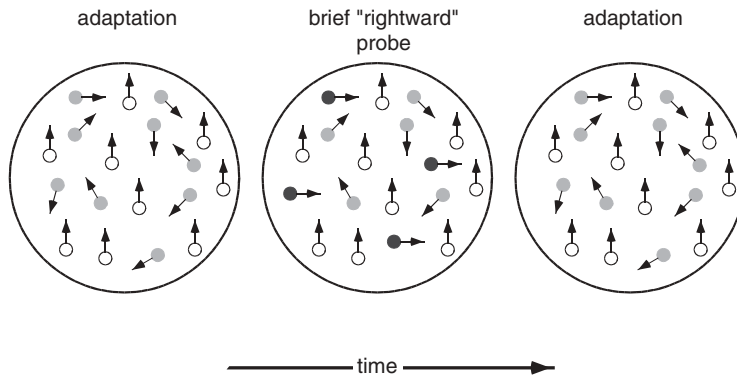


Figure 4.14 Schematic of stimulus conditions used by Alais and Blake (1995) to test attention's influence on motion adaptation.

NOTE: During most of the adaptation period, a subset of adaptation dots moved coherently upward (open circles in left panel), and the remaining noise dots moved randomly in all directions (gray circles in left panel). Unpredictably, a subset of the noise dots moved briefly rightward (black dots in center panel) and then quickly resumed their normal motions (right panel). Observers had to detect this brief motion, which required considerable attention. Note that throughout the experiment all dots were actually the same color; differences of shading are used here for illustrative purposes only.

SOURCE: Modified from R. Sekuler and Blake (2001).

direction, shown as “rightward” in Figure 4.14. The proportion of dots moving rightward was only about 25%, making it necessary for observers to look carefully to detect their presence. On some trials observers were required to indicate when this weak coherent motion was present; on the remaining trials observers simply saw the same stimuli but did not have to perform the detection task and, therefore, did not have to attend selectively to the rightward motion. Alais and Blake reasoned that the first of these conditions would demand more attention than would the second, passive viewing condition. In the passive control condition, the brief insertions of weak rightward motion had little effect on MAE's direction; however, when observers had to attend to it, the inserted motion dramatically altered the aftereffects' direction, shifting it by about 20 deg. This same shift, which was mediated solely by observers' attention to a weak signal, was equivalent to the shift that would have been produced by a very powerful signal (motion with dots 70% correlated). Therefore,

attention to motion in one direction boosted the response to that motion by almost three times, rendering a 25% correlated stimulus as effective as one that was 70% correlated. Extrapolating from neural responses within area MT to changes in degree of stimulus correlation, Alais and Blake deduced that the attentional effects seen in human observers were equivalent, on average, to what would be expected from doubling the stimulus correlation in a nonattended stimulus. There is no doubt that attention can exert a very powerful influence on perceived motion.

Parsing Everyday Activities

Although considerable progress has been made toward an understanding of motion perception, a number of important questions remain unresolved. Among them is the question of how human observers recognize and categorize everyday actions. To clarify the problem, Bobick (1997) has distinguished between what he calls movements, such as the lifting of

arm, and what he calls actions, which include interactions with the environment and other actors, as well as inferred causal relationships among image components. To take just a few examples, actions include a soccer player's heading the ball, a cook's making a cheese sandwich, and your making a bed or ironing a shirt. In all these cases, the actor (the soccer player, the cook, and you) generates a more-or-less continuous stream of movements. An observer's understanding of the visual information could begin with a parsing of the action into distinct perceptual events (Tong, 2001). One perceptual component event could be distinguished from a succeeding component by changes in velocity or in the movement of one body part relative to another. Therefore, motion perception is essential for our ability to parse complex actions. Combining behavioral observations and a novel fMRI paradigm, Zacks et al. (2001) examined motion's possible contribution to action parsing. Participants first watched movies of everyday activities. The movies, 2 min to 5 min long, showed someone making a bed, fertilizing a houseplant, ironing a shirt, or washing dishes. Movies were viewed three times each, in random order. During the first viewing of any movie, observers merely watched the action passively. During this viewing, fMRI measurements were taken. During subsequent viewings of a movie, participants used a button to signal when they thought that one natural and meaningful unit of action had ended and another had begun. During the original, passive viewing of everyday activities, fMRI signals reflected transient changes occurring in several related regions of the brain, including area MT+, which participates in motion perception. The onset of transient changes in neural activity did not occur randomly during the action but were in temporal register with moments that observers deemed to be boundaries between components of the overall action. Thus, it may be that motion information

plays a key role in the segmentation and understanding of everyday actions.

It is worth noting when these transient changes in MT+ activation occurred. On average, they began a few seconds *before* the perceived boundary between action components. As a result, it could be that these anticipatory transient changes in brain activation signify top-down influences, that is, influences of observers' familiarity with the actions and therefore observers' expectancies about upcoming changes in motion. Support for this hypothesis comes from fMRI research with motion that is imagined but not actually seen (Grossman & Blake, 2001; Kourtzi & Kanwisher, 2000).

SUMMING UP AND LOOKING FORWARD

Without question, our understanding of motion perception has been pushed to a level scarcely imaginable just two decades ago. New psychophysical, physiological, and computational research tools have made possible huge strides toward unraveling the mysteries of the visual registration of motion, which Walls (1942) and we consider to be most important among the talents that comprise vision. The application of functional neuroimaging has begun to identify rough but intriguing relationships between particular sites in the visual brain and performance of particular tasks. Obviously, this development has only just started, and many difficult challenges lie just ahead.

Our present knowledge of links between brain sites and aspects of visual motion perception throws only the dimmest of lights onto the complex neural transformations and computations that support performance on various tasks. Motion perception emerges from a shifting partnership between exogenous influences, represented by stimulus attributes, and endogenous influences,

including expectation, attention, memory, and learning. We have relatively little understanding of the parameters and limiting conditions of this partnership. Also, we have no understanding whatever of the control architecture that sets and adjusts the relative weights for the two partners, exogenous and endogenous influences. Furthermore, it is not clear to us whether traditional behavioral paradigms will contribute much to the development of such understanding.

Vernon Mountcastle (quoted in Shadlen & Newsome, 1996) sketched out an ambitious and broad agenda not only for the study of visual motion but also for the entire field of sensory science. He urged researchers to study the complete chain of events that “lead from the initial central representation of sensory stimuli, through the many sequential and parallel transformations of those neural images, to the detection and discrimination processes themselves, and to the formation of general commands for behavioral responses and detailed instructions for their motor execution (p. 628).” This last part of Mountcastle’s unfulfilled agenda would connect decisions about sensory signals to the preparation and execution of motor acts that are appropriate to those decisions, an exciting area in which work has only just begun (see, e.g., Gold & Shadlen, 2001).

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