How We Avoid Collisions With Stationary and Moving Obstacles

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When moving through cluttered environments we use different forms of the same source of information to avoid stationary and moving objects. A stationary obstacle can be avoided by looking at it, registering the differential parallactic displacements on the retina around it during pursuit fixation, and then acting on that information. Such information also specifies one's general heading. A moving obstacle can be avoided by looking at it, registering the displacements reflecting constancy or change in one's gaze-movement angle, and then acting on that information. Such information, however, does not generally specify one's heading. Passing in front of a moving object entails retrograde motion of objects in the deep background; collisions entail the lamellar pattern of optical flow; and passing behind entails more nearly uniform flow against one's direction of motion. Accuracy in the laboratory compares favorably with that of real-world necessities.

We and other animals move through cluttered environments many times each day, often at considerable speed. Most objects in these environments are stationary and need to be avoided if we are to get safely from one place to another. Some objects also move, and these too often must be avoided.[1] Such acts of avoidance are of obvious and considerable importance; to fail to execute them with reasonable accuracy is to risk our daily well-being as well as that of others. What visual information subserves these acts, particularly for mobile-eyed creatures like ourselves?

Psychological research on collisions and how to avoid them began with Gibson and Crooks (1938; see also Gibson, 1961). This research then progressed in several directions. One line has focused on driver behavior and automobile safety (e.g., Caird &

Hancock, 1994; Cohen, 1981; Land, 1992; Land & Lee, 1994; Leibowitz, 1985; Leibowitz & Owens, 1977; Leibowitz & Post, 1982; Probst, Krafczyk, Brandt, & Wist, 1984; Raviv & Herman, 1991; Road Research Laboratory, 1963; Shinar, Rockwell, & Maleck, 1980). Another has been more formal and has pursued an understanding of the information that might specify collisions (e.g., Carel, 1961; Gordon, 1966; Lee, 1976, 1980; Lee & Reddish, 1981; Lee & Young, 1985; Regan & Beverley, 1978; Regan, Kaufman, & Lincoln, 1986; Schiff & Detweiler, 1979; Todd, 1981). The formal treatments generally divide into two categories.

First, the research of Carel, Lee, and those who have followed them has focused on the measurements of when, not whether, a collision will occur. Emphasis has been placed on a variable called time-to-contact and on how this variable is represented in the optical information tau (τ). This information has been measured in many ways but is essentially the instantaneous relative retinal size, or the instantaneous distance of a point in the projection of an object from a fixed point, divided by its temporal derivative. Generalizations of this approach have also looked at time-to-bypass (e.g., Kaiser & Mowafy, 1993; Peper, Bootsma, Mestre, & Bakker, 1994; see also Tresilian, 1994) but have not looked for information distinguishing collisions from bypasses. Research on tau and further derivatives has continued at a lively pace, but with a complex pattern of results (see, e.g., Kaiser & Phatak, 1993; Kim, Turvey, & Carello, 1993; Savelsbergh, Whiting, & Bootsma, 1992; Schiff & Oldak, 1990; Tresilian, 1991, 1994). Second, the research of Regan and his coworkers has focused on whether, but not when, collisions will occur, through motion disparities presented to the two eyes. In essence, according to Regan, an object can be on a path toward one's head only when the motion of its projection in one eye has the opposite sign from that projected to the other and when the object is growing in retinal size. This motion is thus measured binocularly, but stereopsis is not entailed.

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[1] Reciprocally, this same information might be used to capture prey or some other object. Throughout this article, however, we focus on the concept of avoidance.

The information about collisions we wish to pursue is of this latter kind—predicting whether a collision will occur. However, this information is not found in tau, in binocular motion disparities, nor in any related source of information measured by an object's instantaneous relative size or in the relative movement of its edges. Instead, our research is on the relative motions of objects *around* the object on which one is fixated. This information is necessarily used by moving observers; self-motion is not necessarily involved in either the approach of Lee or that of Regan. Indeed, some of the best evidence in support of their claims is based on situations and simulations of what is seen by stationary observers. We make two additional claims. First, tau is relevant only when one already knows a collision or a noncollision will occur; thus, we focus on the prior information that allows a moving observer to determine whether a collision will occur or not. Second, everyday collisions and near-collisions with stationary and moving obstacles can be adequately detected with information presented to one eye.

Differential Parallactic Displacements, Different Tasks, and Directed Perception

In this article, we demonstrate that different aspects of information within the same source are used to avoid stationary and moving obstacles but that they are suitable for different subtasks. With respect to looking at stationary obstacles, we demonstrate in Experiments 1 and 7 that information in the retinal array—differential parallactic displacements and associated information—can be used by the moving observer both for the avoidance of the fixated object and for determining his or her direction of movement.[2] Together, these tasks, when replicated many times, entail finding one's way through an environment. Thus, we have referred to this larger task by the single label *wayfinding* (Cutting, 1986; Cutting, Springer, Braren, & Johnson, 1992). Nonetheless, the first focus of this article is the relation between two subtasks—avoidance of an object and finding one's aimpoint.

What are differential parallactic displacements in this setting? When one is locomoting and looking at an object in the near distance somewhat off the path of movement, wayfinding information is revealed through one or more pursuit fixations of the eye. During such gaze activity, the displacement of near objects is greater than, and in the opposite direction from, far objects. We have previously written this information as an inequality (Cutting et al., 1992, Equation 10):

$$N > -F. \qquad (1)$$

That is, objects nearer than fixation (N, and given positive sign) move faster than, and in the opposite direction from, objects farther than fixation (F). Such opposing displacements specify two things: first, noncollision with that stationary object at fixation (one is looking off one's path of movement, therefore no collision with that object can occur), and second, that the most rapid motion (which, in natural environments, generally occurs for objects nearer than fixation) is in the direction opposite one's direction of movement. Thus, the most rapid motion specifies at least the nominal direction of movement and perhaps the instantaneous angular distance of the aimpoint from

fixation as well (Cutting et al., 1992, p. 59). Our results in Experiments 1 and 7 here extend those of our previous work (Cutting, 1986; Cutting et al., 1992; Vishton & Cutting, 1995).

With respect to looking at moving obstacles, on the other hand, we demonstrate in Experiment 2 that the displacement information on the retina around the fixated object, captured in Equation 1 above, is almost completely useless for determining one's direction of movement, at least in situations of simulated fixation. Despite this, in the second and more important focus of this article, we demonstrate that aspects of differential parallactic displacements remain useful for collision avoidance. That is, in Experiments 3 through 6 we show that collisions and bypasses with moving objects are specified for the moving observer by information reflecting the nonchange or change, respectively, in the angle between one's gaze and one's direction of movement (which we call the *gaze-movement angle*). This information, in turn, is revealed in the relative retinal displacements around the object at fixation.

This dissociation of results within the wayfinding task—determining one's heading and avoiding obstacles—is in keeping with the idea that different information can serve different ends in similar or even identical perceptual situations. We call this idea by the metatheoretical label *directed perception* (Cutting, 1986, 1991a, 1991b, 1993). Directed perception generally contrasts with both the *direct perception* of Gibson (1966, 1979) and *indirect perception*, which Gibson attacked and attributed to many others. Direct perception insists on invariants and one-to-one mappings between stimuli and information regardless of context (e.g., Burton & Turvey, 1990); indirect perception, on the other hand, insists on probabilistic cues and many-to-many mappings between stimuli and information (e.g., Brunswik, 1956; Massaro, 1987; Massaro & Cohen, 1993). Directed perception, in contrast to aspects of both, allows for invariants and other information to specify objects and events, but it also allows for more than one source to be used in a given situation and allows different sources to be used in the same situation but while performing different tasks.

General Method

Stimuli

Stimulus sequences were generated on a Silicon Graphics Personal Iris Workstation (Model 4D/35GT). The Iris is a UNIX-based system with a noninterlaced raster-scan graphics display whose resolution is

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[2] Cutting, Springer, Braren, and Johnson (1992) outlined two sources of information available for wayfinding to a moving observer fixated on a stationary object—differential motion parallax and inward motion. Vishton and Cutting (1995), however, were forced to revise this terminology because they discovered that displacements, not motion, were the bearers of the psychologically relevant information. Thus, the new terms are *differential parallactic displacement* and *inward displacement*. The first means that, when one is fixated on an object in the middle ground, nearer objects generally move in a direction opposite to, and faster than, farther objects; moreover, the direction in which they move is opposite to the direction of the *aimpoint* (the direction of locomotion). The second means that, in the background beyond the fixated object, any object moving toward the fovea is moving in the direction (to the left or right) in which the aimpoint can be found.

1,280 × 1,024 picture elements (pixels). Sequences were generated on-line at a mode of 100 ms/frame, and each trial was 7.2 s in duration.[3] One might think 100 ms/frame would be too slow and would introduce too much temporal aliasing. However, Vishton and Cutting (1995) found that wayfinding performance in relatively naturalistic environments such as those used here was unaffected by frame rates as slow as 600 ms/frame. Moreover, because the motion of most objects generated at pedestrian speeds is quite slow, motion aliasing problems were not bothersome and were generally detectable only with scrutiny. Objects with the fastest motion (and therefore the most visible aliasing) moved across the screen at rates of only about 1°/s, or about 5 pixels per frame; most motion was slower.

Each experiment used a simulated pursuit fixation task (see Cutting, 1986; Royden, Banks, & Crowell, 1992; Van den Berg, 1992; Warren & Hannon, 1990). That is, each trial sequence simulated the forward linear movement of the observer with gaze fixed on an object off to one side. There was no simulated vertical or horizontal oscillation (bounce or sway) of the observer's eye, as used by Cutting et al. (1992) and by Vishton and Cutting (1995) and as found in naturalistic gait. The displays simulated forward translation of the observer at 2.25 m/s, or 1.6 eye heights/s for an individual approximately 1.8 m tall. In Experiments 1 and 7, the object at simulated fixation was stationary (a tree), and in Experiments 2 through 6, it moved (a walking individual or a vertically oriented cylinder sliding across the terrain). Throughout this article we call the walker seen in the display the *pedestrian,* and the participant in the experiment, whose visual field was mimicked while moving at a walking pace, the *observer.* In all cases, the simulated fixation point of the observer during the trial—whether on a tree, the pedestrian, or the cylinder—remained at the level of the horizon and in the center of the screen. Thus, the motions in the display typically simulated the combined camera motions of a dolly (translation) and a pan (a rotation, in this case around the vertical axis). The pan emulated a pursuit fixation on the part of the observer involving eye movements, head movements, or both.

Motion sequences in Experiments 1 and 7 were patterned after those used by Cutting et al. (1992), further simulating the movement of an observer through a tree-filled environment while looking at a particular tree somewhat off of his or her path. In addition, a rectangular grid covered the ground plane and spread into the near distance. It was randomly oriented with respect to the observer, and a new orientation was generated for each trial. Motion sequences of Experiments 1 through 4 also presented the sparse forest and the grid, but in addition they included a pedestrian walking through the forest on the grid. The pedestrian consisted of 13 concatenated rectangular solids: 3 fixed blocks for the torso, 2 fixed blocks for neck and head, and 2 moving and hinged and pivoting blocks for each arm and leg. The movement pattern of the pedestrian was the naturalistic gait of an adult male, following the FORTRAN program written by Cutting (1978b; see also Cutting, 1978a; Cutting, Proffitt, & Kozlowski, 1978), which was extensively rewritten for the Iris in the programming language C. A sample frame of the walker, grid, and forest used in Experiment 2 is shown in Figure 1. On the Iris's color display the pedestrian was yellow, and each of its rectangular solids was trimmed with red edges.

As suggested in Figure 1, there were many small, leafless trees in the environment, each identical in structure. This sparse, wintry forest was created by translating and replicating the same tree to many randomly determined locations across the ground plane. In each location, the tree was then given a new randomly generated orientation by rotating it around its trunk. Scaled to the viewpoint, the first major branching of tree limbs occurred at 1.5 eye heights (2.4 m), and the top of the highest branch was at 2.7 eye heights (4.32 m). The visible horizon was a true horizon for an individual standing on a flat plane. It occurred at a projected distance of about 5,000 m. However, the presence of trees was clipped at 62.5 eye heights (100 m), or about 55 min of arc below the
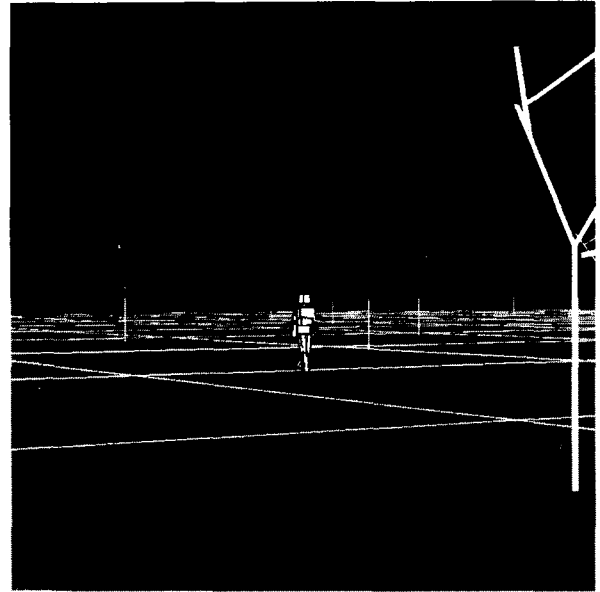

Figure 1. A sample frame from a stimulus sequence in Experiment 2, with a pedestrian and a cluttered surround consisting of a sparse forest and a grid on the ground plane. During the course of the 7.2-s sequence, the motion simulated the movement of the observer through the environment with the observer fixated on the pedestrian, who remained in the middle of the image. In Experiment 1, the same elements were presented except that a fixation tree remained in the middle of the image during the simulated forward movement of the observer and the pedestrian appeared at the edge of the screen and moved toward the fixation tree.

true horizon. In addition, the grid extended out to 25 eye heights but no farther so that we could avoid problems of spatial aliasing seen in lines with marginal slant as projected on the picture plane of a raster system.

Trees were generally gray, the ground plane was brown, the sky was black (the only color available in underlay), and the grid was white. In Experiments 1 and 7, however, the fixation tree in the center of the screen was red so as to offer an easy target to look at. As a trial progressed, the grid and trees expanded and rotated in view, and new trees could appear at, or old ones disappear off of, the edge of the display. Such appearances and disappearances were due either to simulated forward motion of the observer, to pursuit fixation of the observer on the focal tree or pedestrian, or more likely to both.

Procedure

Thirty-three members of the Cornell University community were tested individually in seven experiments. All had normal or corrected-

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[3] With a UNIX system, an operator generally does not have absolute control over timing in a motion sequence; instead, the system will occasionally halt other operations to institute self-cleansing (called "garbage collection"). In our experience with our displays on the Iris, this occurred on average once during every other stimulus sequence. To overcome this timing problem, the graphics community has a standard solution that we implemented: to time the duration of the interrupts and, after each, to restart the stimulus sequence at the location where motion would have been had there been no interrupt. This keeps trial duration constant and motion relatively smooth but varies the number of frames per second and per sequence.

to-normal vision. Most participated in more than one study. Each was naive to the experimental hypotheses at the time of initial testing. They sat in a moderately lit room with the edges of the display screen clearly visible. Viewing was unconstrained and binocular, but participants were strongly encouraged to look at the fixation object and sit 0.5 m from the screen, creating a resolution of 50 pixels/degree of visual angle and an image size of 25° by 20°. Perspective calculations used to generate the stimuli were based on this viewing position and distance.

Observers were told they would be watching stimuli that simulated their own movement across a grid-covered plane peppered with trees and that the stimulus motion would also mimic their fixation on either a stationary object (a red tree) or a moving object (a yellow pedestrian or a yellow, upright, moving cylinder) in the same environment. At the end of each trial the motion sequence ended, but the last frame remained on the screen until the participant made his or her response, which depended on the task. No feedback was given. Six to 12 practice trials, also without feedback, preceded each test sequence. All participants found the task straightforward and naturalistic. Observers were paid $5/hr for their participation.

Methodological Overview of the Experiments

Experiments 1 and 2 are companion studies. In the first experiment, we sought to replicate the wayfinding work by Cutting et al. (1992), presenting displays that simulated linear movement of the observer across a plane through a sparse forest, with the observer's gaze fixed on a central tree. The motions in the display were those generated by a pursuit fixation of the eye and were analogous to the combined camera motions of a dolly and pan. Observers judged the nominal direction of their heading (aimpoint) with respect to the fixation tree. However, unlike in those studies, a pedestrian walked through the scene during the trial, but the pedestrian was incidental to the task. In the second experiment, we used the same environment and the same observer and pedestrian motions, but instead of fixation on a tree, the optics of the trial simulated fixation on the pedestrian. Camera motions of dolly and pan were, again, generally entailed. Final gaze-movement angles, the independent variable of most interest, were identical in both experiments, and the task was the same: At the end of each trial viewers judged whether they were going to the right or to the left of where they were looking (the center of the display screen). The task involved a two-alternative forced-choice procedure.

In Experiment 3, we explored further the information that might be available during pursuit fixation on a pedestrian and set up various parameters possibly involved in perceiving a collision with the pedestrian. The task entailed a three-alternative forced-choice response; the observer judged whether he or she would go in front of, collide with, or go behind the pedestrian. Experiments 4 through 6 are a set of control studies in which we varied the two possible sources of information available for accomplishing the collision detection task—the presence or absence of self-occlusion information within the contours of the moving object during its relative rotation with respect to the observer, and the presence or absence of motion in the foreground and background.

Experiment 7 reverted to the character of Experiment 1, simulating pursuit fixation of a stationary object (a tree), but we used a three-alternative forced-choice procedure as in Experiments 3 through 6. Observers judged whether they were going to the left or right of a tree or if they were going to collide with it. The purpose of this study was to compare the general accuracy of collision detection for stationary targets with that for moving ones.

Experiment 1: Wayfinding While Fixated on a Tree, With an Incidental Pedestrian in View

The first experiment served as a necessary control for Experiment 2. Here, as a small elaboration of previous wayfinding studies in this research program (Cutting, 1986; Cutting et al., 1992; Vishton & Cutting, 1995), the stimulus sequences entailed simulated fixation on a stationary object (a tree), but with the pedestrian used in later studies strolling through the scene. This pedestrian served as a potential distractor and as a body not rigidly connected to the environment. Our previous analyses of wayfinding ability, and those of most other researchers, have assumed and used a completely rigid surround.

Method

Stimulus sequences mimicked forward movement of an observer looking at a red fixation tree (always at the center of the screen) in a small gray forest planted on a rectangular grid in brown soil and with a black sky. At the end of the trial, the fixation tree was at a distance of either 7.8 or 15.7 eye heights, as measured along the observer's path and orthogonal to it. Starting either at the beginning or near the middle of the trial sequence, the pedestrian appeared and walked through the scene directly toward the central fixation tree. Nonetheless, the display remained as if the observer was still fixated on the tree. The pedestrian approached the fixation tree from one of eight different angles on the ground plane—0, 45, 90, 135, 180, 225, 270, and 315°, where the 0 and 180° paths were parallel to that of the observer, the 180° path was toward the observer, and 90° was from the right.

At the end of the trial, all motion ceased and the last frame in the sequence became a static display that remained on the screen until the observer responded. The observer's task was the same as that used by Cutting et al. (1992): The observer discerned his or her direction of movement, to the left or the right, with respect to direction of gaze (at the fixated tree). At the end of the trial, he or she pressed a button on the Iris mouse, left or right, to indicate direction of locomotion with respect to the tree. If an observer wished to view a trial again, he or she could press the middle mouse key, but few participants elected to see any trials a second time. All viewers found the task comprehensible and reasonably natural.

The major independent variable in this experiment was the final angle between the simulated observer's gaze and his or her simulated direction of movement (final gaze-movement angle). Trials presented initial gaze-movement angles of 0.67, 1.34, 2.67, or 5.35° for the nearer fixation distance and of 0.8, 1.6, 3.21, or 6.41° for the farther fixation distance. During the course of the trial this angle increased until the final gaze-movement angles were 1, 2, 4, or 8°.[4] Because trial duration was 7.2 s, the most rapid, mean simulated eye (or head) rotation rate was 0.22°/s, well within the performance limits suggested by Royden et al. (1992) for accurate heading judgments with simulated eye (or head) movements. A sample layout of the observer in the environment with a final gaze-movement angle of 16° (twice the largest value used in this study) is suggested in the left panel of Figure 2, but without the pedestrian.

Eight observers participated. Each watched a different random sequence of 256 trials: 2 distances from the fixation tree × 8 differently oriented pedestrian paths × 4 final gaze-movement angles × 2 gaze directions (to the left and to the right) × 2 replications of each with differently placed trees and a randomly rotated grid.

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[4] Vishton and Cutting (1995) argued that the initial gaze-movement angle was a more appropriate measure of accuracy, because the period of time during which information about aimpoint accrues includes the reaction time interval (typically at least 3 s). Whereas we concur with this assessment, these experiments were conducted prior to those, and the experimental variables reflect those established first by Cutting et al. (1992).
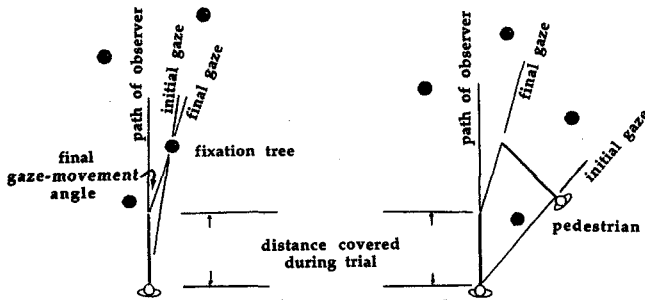
Figure 2. A schematic, overhead view of the layout of trials in Experiments 1 and 2. In the left panel, an observer is shown to move through a cluttered environment with pursuit fixation on a tree. The final gaze-movement angle indicated is 16°, larger than that used in any of the experiments here. In the right panel, an observer moves through a cluttered environment with pursuit fixation on a moving pedestrian. Again, the final gaze-movement angle indicated in the panel is 16°. Notice that final gaze-movement angles in both experiments were the same, and the observer's task was the same: to judge his or her direction of movement, left or right, with respect to simulated gaze.

Results and Preliminary Discussion

As in all of our previous studies, there was a reliable effect of final gaze-movement angle, $F(3, 21) = 11.6$, $MSE = 14.56$, $p < .0001$. That is, performance increased as a function of the increase in the final gaze-movement angle, as shown in the top function in the left panel of Figure 3. In addition, there was also a reliable effect of final distance between the observer and the fixation tree, $F(1, 7) = 10.4$, $MSE = 5.35$, $p < .015$, with overall performance being superior for trials ending with fixated trees at nearer distances (88% vs. 81%). Both effects can be seen in the middle panel of Figure 3. As expected, there was no effect of the pedestrian's approach angle, $F < 1.0$, with overall performance on each of the eight approaches falling between 83% and 85%.

Wayfinding performance in the presence of a moving object. The upper gaze-movement angle function in the left panel of Figure 3 is no different than those found in our previous work (Cutting et al., 1992; Vishton & Cutting, 1995). This lack of difference contrasts with a result of Warren and Saunders (1995). Simulating observer motion through a dot cloud with a secondary, laterally moving object, they found that heading judgments were displaced by as much as 3.4° if the heading could not be seen. Here, simulating observer motion through a forest with full information about relative size of objects, height in the visual field, and occlusion, we found that observers had no difficulty even though the true heading was occluded by the pedestrian during the sequence on nearly half the trials.

Three differences in the methodology may have caused this effect: (a) In our study we used a nominal direction task (observers simply judged if they were looking right or left of their aimpoint), whereas Warren and Saunders (1995) used an absolute judgment task (observers were probed at the end of a trial about where they thought their heading was); (b) the Warren and Saunders object was usually considerably larger than our pedestrian; and (c) our additional sources of information (relative size, height, and occlusion) served to disambiguate the layout sufficiently so that such biases did not occur. The results

of Cutting, Vishton, Flückiger, and Baumberger (1995) suggest that the task differences are not the cause; they found no differences between nominal and absolute judgment tasks in observers' ability to determine their aimpoint. In addition, analysis of the size of the pedestrian at the end of the trial (the pedestrian was much larger in the near condition than in the far condition) was exactly the same as the distance effect. This means that wayfinding performance here was better with a larger moving object and when it occluded the aimpoint for a longer period of time. Thus, the difference in object size in our study versus that of Warren and Saunders (1995) is not likely to have caused the effect. This leaves the third possibility, which we endorse, that the use of forests versus dot clouds is likely to have caused the difference and that the additional sources of information in relative size, height in the visual field, and occlusion information in our study aided observers' performance.

Wayfinding and pursuit fixation distance. The distance effect is gratifying and new. Heretofore, we had not systematically varied the final distance between observer and fixation tree, but we had often found performance on some tasks better than on others (see, e.g., Cutting et al., 1992, Experiment 1 vs. Experiments 2 and 3). It is now clear that these differences were due to variations in fixation distance, better performance occurring for nearer fixation trees. This effect is undoubtedly caused by the increase in retinal velocities of nonfixated objects in both the foreground and background when an observer looks at a relatively nearby object. This increase is, in turn, most likely caused by the increase in eye or head rotation (or both) entailed in the pursuit fixation of a nearby object, a result counter to what might be predicted on the basis of the results of Royden et al. (1992). Cutting et al. (1992) and Vishton and Cutting (1995) estimated that observers traveling at 2.25 eye heights/s would need to judge their aimpoint within 3.33° of visual angle; such performance was achieved here (or nearly so) only in the near-tree condition. We should note, however, that because the trial ended with the fixation tree still 7.8 m distant
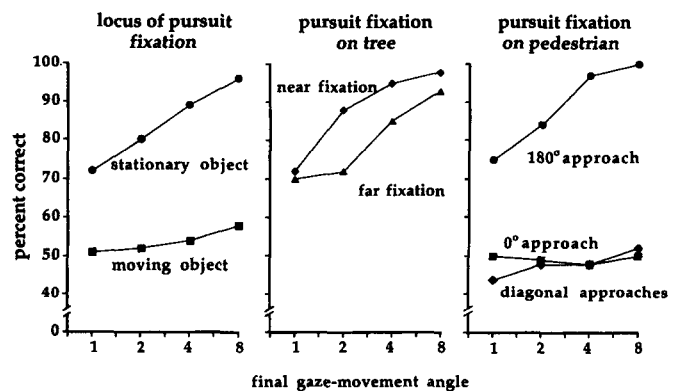
Figure 3. Results from Experiments 1 and 2, with pursuit fixation on a stationary tree and on a moving pedestrian, respectively, as a function of final gaze-movement angle. The left panel shows the overall results of both experiments; the central panel shows the results of Experiment 1 for the two conditions with fixation trees at different distances, with trials ending relatively near and far from the fixation tree; and the right panel shows the results of Experiment 2 for the eight approach conditions of the pedestrian.

(and farther than in, e.g., Cutting et al., 1992, Experiment 1) there was still ample time (3.5 s) for a potential collision with it to be avoided.

Alternative Accounts

Although these results are consistent with our account, we cannot conclude on the basis of these data alone that stationary obstacle avoidance is done on the basis of differential parallactic displacements. At least four other accounts have been proposed, and we need to consider them.

Looming and tau. First, in a single paragraph, Gibson (1966) proposed what have become two separate sources of information about collisions that have subsequently been investigated by others. He proposed that if the form toward which an observer wishes to go "is the right form—if it specifies prey, or a mate, or home—all he has to do is magnify it in order to reach the object. He governs the muscles of locomotion so as to enlarge the form, to make it loom up" (Gibson, 1966, p. 162). However a good source of information looming (and tau) is for timing a collision, it is by itself a poor distinguisher of collisions from bypasses (Kaiser & Mowafy, 1993; Tresilian, 1994). We return to this idea after presenting Experiment 2.

Alignments of target and the focus of radial outflow. Second, and continuing his presentation, Gibson (1966) also proposed, "The same rule of visual approach holds true for swimming, flying, or running: keep the focus of centrifugal flow [sometimes called the focus of radial outflow, or the focus of expansion] centered on the part of the pattern of the optic array that specifies the attractive thing or the inviting place" (p. 162) one wishes to attain. Reciprocally, to avoid such a thing or place, one need only remove it from the focus of radial outflow. In the late 20th century, this would appear to be the received view in visual science on guidance of locomotion and on wayfinding, but we disagree with it. We think the focus of radial outflow is extremely difficult to find under conditions of pedestrian locomotion. To obtain the focus of radial outflow one must, for mobile-eyed creatures like ourselves who tend rarely to look exactly where we are going, decompose the pattern of flow on the retina into at least two components—the rotational flow that is due to eye or head movements and the translational flow that is due to the observer's moving through space (see, e.g., Hildreth, 1992; Koenderink & Van Doorn, 1987; Longuet-Higgins & Prazdny, 1980; Rieger & Lawton, 1985; Van den Berg, 1992; Warren, Morris, & Kalish, 1988). Although much research is associated with this idea and has claimed to corroborate it, the focus of the work in Cutting et al. (1992) was to cast it in doubt and to propose a new system based on differential parallactic displacements. We do not repeat those arguments here but simply point out that there is, at present, no workable psychological theory, encompassing radial outflow or not, that predicts four kinds of events—collisions and bypasses with stationary and moving objects. What we plan to present here is a coherent theory encompassing all four.

Eye movements. Third, if one wanted to head directly for an object, one could, in principle, simply place the target in the center of the visual field and align one's translation vector with this target. Drifts of the position of the target from midfield could be fed into a system correcting one's locomotion vector,

and new measurements could be made. This idea is inherent in the work of Calvert (1950, 1954) and of Llewellyn (1971), who called it "drift cancellation," and it works well for robots (Huttenlocher, Leventon, & Rucklidge, 1994). Contrarily, if one wanted to avoid an object, one need only be assured that the object under consideration did drift. There are three problems with this idea. First, even when dealing with a potential collision (unless it is imminent), people rarely look directly in the direction they are headed, so the gaze vector and the heading vector are rarely aligned. Second, if the target is off one's path but one fixates it and pursues it for some time, it does not drift in the field of view (Regan & Beverley, 1982). Instead, it drifts only as measured through eye movements. If such drifts alone served as the proper source of information, then the threshold for motion detection ought to be the same for a moving object with and without other, stationary objects in view. Aubert (1886) and Leibowitz (1955), among many others, showed that motion detection is as much as an order of magnitude better with surrounding stationary objects, thus implicating the relative motion of objects in the field of view as a more potent source of information than eye movements. It is the pattern of this relative motion in three-dimensional space around a fixated object that is inherent in differential parallactic displacements.

Binocular, opposed motion. Finally, Regan and Beverley (1978) claimed that in a collision any edge or identifiable central point on a moving object will have binocular motions of opposite sign (i.e., it will move leftward on the left retina and rightward on the right retina). Bypasses are specified by same-signed motions, either leftward in both eyes or rightward. Their research, however, concerned the rapid approach of relatively small objects, such as a cricket ball toward a batsman. Unfortunately, in their research, they made several assumptions to which we do not subscribe. First, their collision and noncollision velocities are quite high, well above any speed attainable on foot. Thus, their paradigm implies a stationary observer and a ballistic object moving toward him or her and negates the study of the moving observer, at least as a pedestrian. Second, the geometry of their situation assumes either that some point on the object can be tracked, which, because of spin, is unlikely for a cricket ball or a baseball, or that the edges of the object are registered, which further constrains the situation to the consideration only of objects with a diameter smaller than the distance between one's eyes. Besides, potential collisions with a stationary object can clearly be detected, as we show in Experiments 3, 4, and 7, with cinematic information, which simulates that available to only one eye.

Overview

The major point of Experiment 1 was as a replication of the work of Cutting et al. (1992) with the addition of an incidental pedestrian in the field of view. As in that article, the results here imply two complementary findings: (a) Observers can determine their direction of movement with about 95% accuracy within 3.33° of visual angle, the requirements calculated to be appropriate by Cutting et al. (1992) for a velocity of 2.25 m/s, and (b) observers have sufficient information and time to avoid a stationary obstacle. Thus, information for direction finding and collision avoidance are necessarily yoked in this task. More-

over, and happily, performance was unperturbed and undiminished even in the presence of an object (the pedestrian) not rigidly connected to the environment. As expected, the segregation of a pedestrian from a rigid environment is done easily and without measurable effect on task performance. This study, then, served as a control and background for Experiment 2, in which the pedestrian was no longer incidental.

Experiment 2: Attempts at Wayfinding While Fixated on a Moving Pedestrian

In Experiment 1, we demonstrated that moving observers can determine the direction of their aimpoint with considerable accuracy when fixated on a stationary object in the visual field despite the presence of a moving object that might distract them. In this second experiment, we addressed the possibility of an observer's accomplishing such a feat while fixated on that moving object.

Method

The observer's path through the sparse forest and over the grid was identical to that in Experiment 1. However, this time, rather than the pedestrian's being incidental, the display simulated the observer looking directly at the pedestrian throughout the trial. This new gaze situation, like that in the previous study, also constituted camera movements of both dolly and pan, but the pan in this case did not follow a stationary object. The general spatial pattern of movements and gaze for a given trial is suggested in the right panel of Figure 2; a single frame is shown in Figure 1.

The pedestrian's path ended on the left or the right of the observer, and the pedestrian traversed a trajectory at 0, 45, 90, 135, 180, 225, 270, or 315° to the observer's path, as suggested in Figure 4. In discussion of the results below and in Experiment 3, we collapse across approaches to the left and right and call the 45 and 135° cases *acute approaches,* the 90 and 270° cases *perpendicular approaches,* and the 135 and 225° cases *obtuse approaches;* together the acute and obtuse are called *oblique approaches.* On three eighths of the trials the pedestrian crossed over the observer's path, and on others the pedestrian stayed on the originating side; on half of the trials the pedestrian ended on the right side of the observer's path, and on half the pedestrian ended on the left. Figure 4 shows pedestrian paths always ending on the right, with a final gaze-movement angle of 16° (again, a gaze-movement angle larger than any used in this study). Most important, when the trial was over and the static display remained on the screen, the pedestrian was in exactly the same position as the fixated tree in a corresponding trial in Experiment 1. Thus, final gaze-movement angles in this study and in the previous one were matched and identical; initial and intermediate gaze-movement angles, on the other hand, were always different. Eye/head rotation rates during simulated pursuit fixation varied across trials. Those for 0° approaches (i.e., following the pedestrian) were always 0°/s (there was no simulated eye/head rotation). For near and far pedestrians, respectively, the mean eye/head rotation rates for 180° approaches were 0.3 and 0.2°/s; for the perpendicular approaches they were 2.5 and 1.5°/s; for the obtuse approaches they were 1.5 and 0.9°/s; and for the acute approaches they were 2.4 and 1.3°/s.

The same 8 observers participated here as in Experiment 1, immediately following that experiment. Again, each watched a different random sequence of 256 trials: 2 distances from the pedestrian × 8 pedestrian paths × 4 gaze-movement angles × 2 gaze directions (to the left and to the right) × 2 replications of each. Instructions were explained to the observers with great care; all knew the task was the same as in the previous study: They were to judge the simulated direction of their own
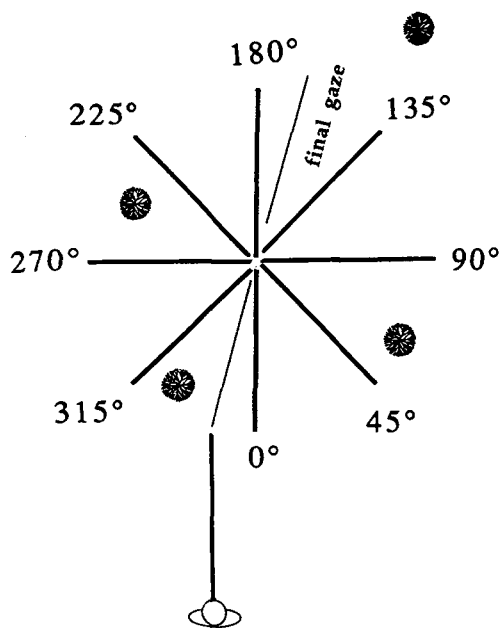

Figure 4. A schematic, overhead view of eight possible paths of the pedestrian in Experiment 2, scaled to the near-distance condition. In the far-distance condition, the observer was moved back twice the distance from the final position of the pedestrian, but with final gaze-movement angles retained. In this figure, all approaches end to the right of the observer; an equal number of similar trials ended with the pedestrian to the left of the observer. The final gaze-movement angle indicated is 16°, but again the largest angle used in the experiment was 8°.

movement, not that of the pedestrian, with respect to the instantaneous position of the pedestrian at the end of the trial.

Results and Discussion

Overall results were strikingly different here than in the previous experiment, as shown by the lower function in the left panel of Figure 3. Performance was nearly at chance throughout the task, and there was no reliable effect of final gaze-movement angle, $F(3, 21) = 1.17, p > .30$. There was also no reliable effect of distance, $F(1, 7) = 2.07, p > .15$, with aimpoint correctly determined while looking at near pedestrians on 53% of all trials and while looking at far pedestrians on 55% of all trials. Both of these overall results are null here and contrast with those in Experiment 1.

However, as shown in the right panel of Figure 3, there were striking differences in wayfinding performance across the different approach paths of the pedestrian, $F(7, 49) = 14.10$, $MSE = 0.237, p < .001$. This is also in contrast with the results of Experiment 1. When the pedestrian was walking directly toward the observer (180°), the case analogous to driving a car into oncoming traffic on which one is fixated, overall performance across all such trials was quite high (89%); for all seven other pedestrian paths, however, performance was dramatically worse, averaging 49% and with a range from 47% to 51%. We then compared the major results of these first two experiments and found a reliable difference in performance across them, $F(1, 7) = 43.5, MSE = 188.9, p < .0001$, as shown clearly in

the left panel of Figure 3. There was also a reliable Experiment (gaze on stationary vs. moving object) × Final Gaze-Movement Angle interaction, $F(3, 21) = 6.36$, $MSE = 3.65$, $p < .003$, which reflects an increase in performance with final gaze-movement angle for the data of Experiment 1 that was not found in the data of Experiment 2.

The results of Experiment 2 genuinely surprised us. When we interviewed our observers after the experimental sessions, we found that all felt they performed about equally well in the two studies. Indeed, when we ourselves performed the two tasks, our confidence in our performance on trials in Experiment 2 was about the same as that in Experiment 1. Parameters and layout were carefully recalculated and nothing was found amiss. Nonetheless, although observers can decisively determine their aimpoint when fixated on a stationary object, in our situation they generally do not know where they are going when fixated on a moving object. This result contrasts with some in the literature (Royden et al., 1992; Van den Berg, 1992), so we must consider the results of this study in more detail.

Facing oncoming traffic. Performance with the pedestrian on the 180° path was high (89% overall) and meets wayfinding requirements outlined by Cutting et al. (1992). In fact, performance in this condition was slightly, although not statistically, better than that for the fixated-tree condition (84%) in Experiment 1, $F < 1.0$. Combining the data across Experiments 1 and 2, we found reliable distance effects only with these two 180° conditions, with performance for near-fixated objects (89%) better than that for far-fixated objects (84%), $F(1, 7) = 11.08$, $MSE = 0.086$, $p < .013$. Mean simulated eye/head rotation rates, again, were 0.3 and 0.2°/s, respectively, for near and far objects. There was also a reliable three-way Experiment (stationary vs. moving object at fixation) × Distance × Final Gaze-Movement Angle interaction, $F(3, 21) = 3.85$, $MSE = 0.076$, $p < .03$, in which observer performance while looking at near pedestrians at small gaze-movement angles was considerably better than that in the three cases of observers looking at far pedestrians and both near and far trees.

To be sure, it is gratifying that on the basis of motion information alone, one can determine one's aimpoint in the face of oncoming traffic, that is, when looking at moving objects on a path parallel but opposite (at 180°) to one's own. On such trials, differential parallactic displacements and inward displacements are identical in general character to those found when looking at a stationary object, except that here the velocities of near and far objects instantaneously move twice as fast in the retinal field. This increased velocity probably accounts for the marginally better performance in this condition than in the cases with a stationary object at fixation in Experiment 1. Finally, the more-than-satisfactory performance on these 0° trials indicates that our observers understood the overall task they were performing; had they not, and had they mistakenly judged the direction of the pedestrian, their performance would have hovered near 0% at large gaze-movement angles. Thus, it seems unlikely that the generally poor performance on the other types of trials can be attributed to a misunderstanding of instructions.

Looking at pedestrians on paths oblique or perpendicular to one's own. Poor performance on the four oblique and two perpendicular paths is consistent with our theory (Cutting, 1986; Cutting et al., 1992; Vishton & Cutting, 1995). The differential

parallactic displacements and inward displacements (the displacement of far objects toward the fovea and in the direction of movement) do not systematically follow the rules for information about finding one's way. That is, when one fixates on a stationary object, the other objects in the foreground generally move faster than, and in the opposite direction from, those in the background. When one fixates a moving object, however, this opposition often does not occur, and indeed in this experiment never occurred for fixations on an object moving along an oblique or perpendicular path in front of the moving observer. In particular, on all such trials in this experiment both foreground and background textures moved in the same direction. This fact may have contributed to the strong bias in the observers' results for these trials—that is, they almost always said that their aimpoint was in front of the pedestrian, even though on half of the trials it was behind. This bias is in the same direction as that of Royden et al. (1992) and also explains why overall performance hovered near 50%.

Mean simulated eye/head rotation rates were 1.65°/s across all oblique and perpendicular approaches. Royden et al. (1992) found that simulated rotations generally greater than about 1°/s decreased performance when compared with real rotations. It is possible that the relatively fast simulated rotations may have depressed performance somewhat, but it seems unlikely that performance would have fallen completely to chance levels for all gaze-movement angles. Moreover, Cutting et al. (1995) found quite different results using dot-cloud stimuli like those of Royden et al. (1992) versus forest stimuli like those used here. The next category of trials also speaks to this issue.

On a path following traffic. Particularly interesting and surprising to us, however, was the performance with the pedestrian on a path at 0° to that of the observer (i.e., in front and on a parallel path). We did not expect that performance here would be at chance nor be the same as on the oblique and perpendicular paths. This result is important because the global motion presented in this condition (and in this condition alone) was identical to the translational flow field as used, for example, by Warren and Hannon (1990) and by Cutting et al. (1992, Experiments 6-9) with the exception of the presence of the pedestrian.

There are at least two ideas in the literature one might propose that cannot account for these data. First, Royden et al. (1992) found systematic differences in heading judgments between conditions simulating eye movements and those in which real eye movements were entailed. Such differences occurred when simulated eye movement exceeded 1 or 2°/s, but not when it was less. However, unlike the other seven conditions in this experiment, there was no simulated rotational component in the display that was due to eye movements. By extension and because of the similarity of results, it then seems unlikely that the poor performance in the oblique and perpendicular approaches was due solely to artifacts in simulated eye/head rotation rates. Second, Warren and Saunders (1995) found that aimpoints were misestimated when they were occluded by an object. However, our result cannot be attributed to this factor because such occlusions occurred only on one eighth of these trials—in the near condition and then only at a gaze-movement angle of 0.5°.

The reason for poor performance in this condition is not

completely clear, but we have checked the geometry of the situation and replicated the result. Perhaps the mere presence of the pedestrian is a distraction here, but not in the 180° condition, sufficient to impede performance, although this explanation seems complicated and unlikely to us. Perhaps the observer expected the display to simulate eye movements on such trials as on all other trials, when in fact it did not; but this account is little more than a redescription of the camera movements entailed in these displays. Perhaps, however, the viewers' attention was drawn away from the aliasing artifacts inherent in raster-scan optical flow displays (see Cutting et al., 1992), and therefore there was no residual artifactual aid for wayfinding. This account seems plausible to us, but as yet we have no concrete evidence in its favor.

Same Setting, Different Tasks, Different Information From the Same Source

With respect to observers' determining their direction of movement, the results of Experiments 1 and 2 are strikingly different. When observers are fixated on a stationary object, their ability to find their aimpoint is good and adequate to the task. When observers are fixated on a moving object, on the other hand, our results suggest that generally they have no clue where they are going. Of course, in the real world when one traverses a path for some length of time and looks at various objects, both stationary and moving, one can remember the general location of one's aimpoint across fixations and other eye movement behavior. Nonetheless, within the constraints of our experimental task, what our results suggest is that, during pursuit fixation on a moving object, there is no new information that accrues about one's aimpoint, unless one happens to be looking at oncoming traffic. Such cleanly divergent results across the two experiments suggested to us that one is necessarily performing different arrays of subtasks when looking at stationary and at moving objects.

On the surface, these results, if generalizable to the natural situation, may seem to raise a potential conundrum: When walking or driving, people obviously and consistently look at moving objects for some period of time. If there is no information available to us about our direction of movement when we fixate on a moving object—if we do not know where we are going—why then do we ever look at such objects? The answer, of course, seems likely to have to do with one of the other subtasks of wayfinding—collision avoidance.

On the Geometry of Collision Detection Without Knowledge of Headings

The ability to avoid a collision with a moving object is an important skill. How might such collisions be detected? One possibility concerns the variables associated with time-to-contact. Discussions of the information specifying time-to-contact stem from Hoyle (1957), Carel (1961), and more particularly the work of Lee (e.g., 1976, 1980) and his associates. The variable in question has been called tau, but more recently taus have speciated and at least two varieties can be isolated that are pertinent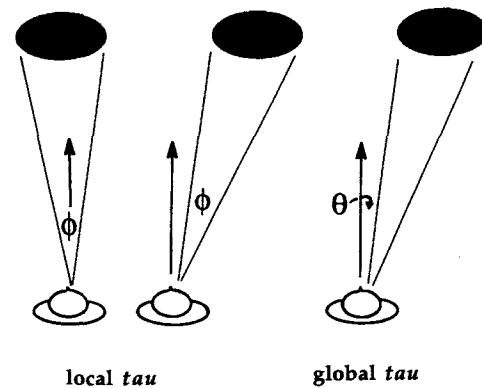 here. One is local tau (τ_L), which can specify the time-to-contact between a moving object and a moving pedestrian;

local *tau*   global *tau*

Figure 5. Three geometric constructions to be used with Equations 2 and 3 for the consideration of both local tau (τ_L) and global tau (τ_G) as possible, but unlikely, sources of information for observers to use in discriminating between collisions and bypasses. The growth in the angle θ for τ_L, as shown in Experiment 6, is not an adequate predictor of collisions from bypasses, and the growth in the angle ϕ for τ_G is dependent on the moving observer's knowing his or her heading, which in our situation the results of Experiment 2 show is unknown.

the other is global tau (τ_G), which can specify the time in which a moving object and a moving pedestrian will pass one another, sometimes called the time-to-bypass (Kaiser & Mowafy, 1993; Tresilian, 1991). The equations are similar in form:

$$\tau_L = \phi/(\delta\phi/\delta t) \qquad (2)$$

and

$$\tau_G = \theta/(\delta\theta/\delta t), \qquad (3)$$

where under conditions of contact, ϕ is the instantaneous angle between two points on an object converging on the observer, and under conditions of bypass, θ is the angular deviation between an edge or the centroid of the object and the observer's path (or a path parallel to that of the object, if it is moving and not the observer). The denominators of both equations concern the derivative of these angles with respect to time (t). The spatial relations for each are suggested in Figure 5.

The problems in applying these equations to situations of judging the difference between collisions and bypasses are several. First, τ_L fails to distinguish adequately between the two cases; that is, in collisions and near-collisions related to them, the expansion of the object on a given retina occurs with nearly identical functions. In Experiment 6, we demonstrate this empirically. Second, τ_G is calculated using θ, an angle equivalent to our gaze-movement angle, which our Experiment 2 suggests is unknown to the observer in a collision situation, at least with the motions of a simulated fixation. The method suggested by Peper et al. (1994) also assumes that a measure like θ is known and fails in our situation for similar reasons. Third, to distinguish between collisions and bypasses one must be able to distinguish between situations in which τ_L and τ_G apply. This might be done on the basis of drift of the target or on the basis of binocular motion information. As noted in our discussion after Experiment 1, drifts are detected much better in the pres-

ence of other, stationary objects, which in turn can mimic some of the properties of differential parallactic displacements; and the efficacy of opposed binocular motions applies only to objects moving relatively faster than human locomotion allows and to those of a size smaller than the width between the eyes. Thus, we claim the difference between τ_L and τ_G is not adequately specified in one eye without consideration of relative motions of a moving target to stationary ones.

At issue, then, is the following question: If we do not know where we are going, how can we detect a potential collision? Consider the situation shown in the upper left panel of Figure 6. The observer is moving through an environment, and another person (or car, train, or plane) is moving as well. If four conditions are met, a collision will occur: (a) if both observer and moving object maintain constant velocity, (b) if both are on linear paths, (c) if they maintain a constant gaze-movement angle between them, and (d) if the retinal size of the object increases for the observer. The training of airline pilots and other fliers includes the constant gaze-movement angle strategy for detecting collisions. Pilots are told that if another aircraft stays in the same location through their windscreen and grows large, they should immediately take evasive action. Kaiser and Mowafy (1993, Figure 9) noted this relation as well, but in the context of τ_G discussed above. Constant gaze-movement angles have proved useful for other creatures. For example, Lanchester and Mark (1975) noted that some feeding fish keep a constant gaze-movement angle between their path and their food as it descends through the water.

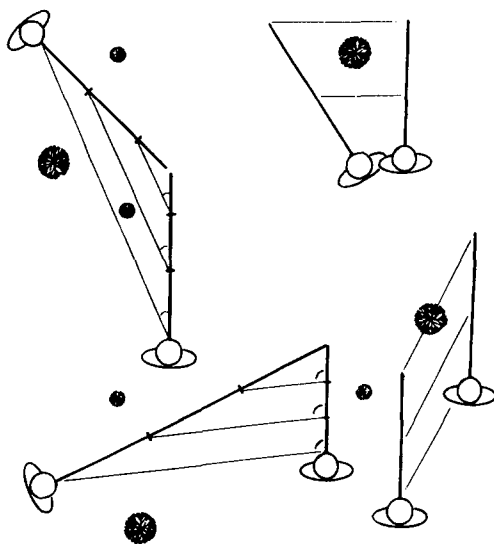The other three panels of Figure 6 explore the generality of

Figure 6. Four situations in which two pedestrians are on collision or noncollision courses. In the top left and bottom left panels, notice the constant gaze-movement angles before the collision occurs. For a collision to occur in this type of situation, the two individuals must be on linear paths and moving at constant velocity, but they do not need to be moving at the same velocity. In addition, the retinal size of one individual must be growing for the other. The upper right panel shows a situation where retinal size decreases, and the lower right panel shows one where retinal size stays the same. Collisions would occur in neither case.

this claim for collisions in this type of situation. In the lower left panel, one can notice that the two observers need not be moving at the same velocity; that is, they can move at different constant velocities and a collision will still occur. The situation in the upper right panel shows that when retinal size decreases, no collision will occur because the two objects are on diverging paths, and the situation in the lower right panel shows that when retinal size remains constant, they are on parallel paths. Thus, these panels explain the necessity of condition (d).

Notice an interesting and important fact. Within this geometric construction of the situation, if a moving observer can detect the constancy of the gaze-movement angle, he or she has the potential for detecting a collision even if he or she does not know his or her own aimpoint, or direction of locomotion, and even if he or she does not know the aimpoint of the object. Thus, in our view, the two paths of movement need not be perceived or constructed prior to determining whether or not a collision will occur. The fact of a collision falls out of the geometry of the setting, not out of computation of movement paths. The issues, of course, are whether and how this geometry might be represented in the optical array.

On the Nature of Differential Parallactic Displacements for Collisions and Bypasses With Moving Objects

As in our previous work (Cutting et al., 1992; Vishton & Cutting, 1995), we are committed to the idea that wayfinding information generally, and collision and bypass information more particularly, is in the registration of displacements on the retina. We call these differential parallactic displacements because different velocities occur at different distances in depth around an object under fixation. How do they manifest themselves in collisions and bypasses with a moving object?

Passing in Front

Let us consider first situations where the observer passes in front of the moving object. In such a case, as shown in the left panels of Figures 7 and 8 for an approach from the right, there are some similarities with the situation of looking at a stationary object. That is, the information in differential parallactic displacement is that objects in the foreground (N, for near) move rapidly in the direction opposite to the observer and that objects in the deep background (VF, for very far) move more slowly with the observer, in retrograde motion. This can be captured as

$$N > -VF. \tag{4}$$

Notice that this inequality is very similar to Equation 1. It is different in that when one is looking at a stationary object, all other objects, whether immediately behind the fixated object or in the deep background, move with the observer. When one is considering the possible interactions with a moving object, it is only in cases of frontal bypass that this retrograde motion occurs, and thus in potential collision situations this is a foolproof source of information about noncollision.
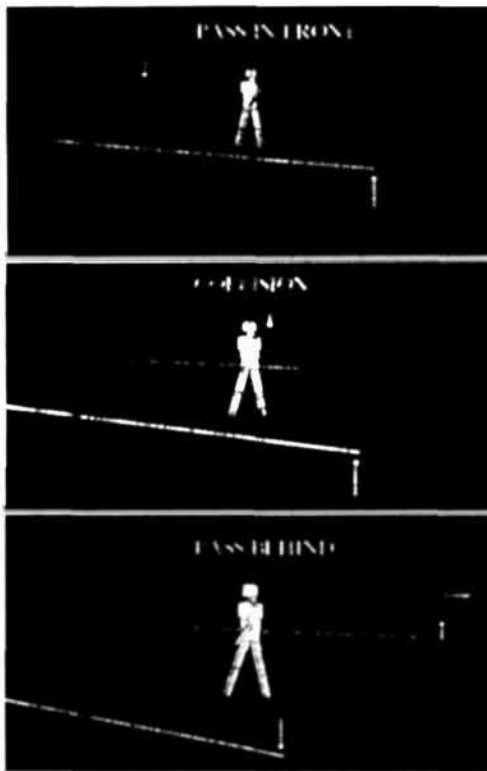
Figure 7. Representations of the geometry of retinal displacements when an observer is passing in front, colliding with, and passing behind a pedestrian. In each case, the pedestrian is approaching from the right and will intersect the path of the observer at an angle of 90°. Each panel shows the pedestrian after seven (of nine) step cycles during near-distance trial sequences used in Experiment 3. The foreground and background show the field of displacements for a grid of points in the three conditions during the first seven step cycles. When the observer is passing in front of a moving, fixated object, there is retrograde motion of the background in the same direction as the observer's movement, whereas foreground objects move against the direction of the observer's movement. Arrows indicate the most recent trace of two vectors, one in the near ground and one in the far ground. This is shown most clearly by the array of displacements immediately to the left of the pedestrian. When the observer is on a course that will collide with the pedestrian, the displacement pattern in the foreground and background is lamellar in the same direction, against the observer's direction of movement, and decreases with the reciprocal of distance. When the observer is passing behind the object, the flow is nearly uniform regardless of depth.

Collisions

During fixation with a constant gaze-movement angle, the displacement of objects and textures on the retina follows the character of pure translational flow. That is, because there are no eye movements (or head movements), the pattern of displacements during linear movement is symmetric and radially outward from the moving observer's aimpoint at the horizon. Because one is looking off to the side, however, these displacements are asymmetric on the retina, but all motions of objects and textures in the environment are linear (actually, portions of great circles in the spherical array) and lamellar.

In addition, again because there are no contributions of eye movements, the velocity of these motions is the reciprocal of distance. That is, if objects instantaneously at one eye height move at one unit/second, those at two eye heights move in the same direction half as fast, those at four eye heights move in the same direction one quarter as fast, and so forth. These relations are the differential parallactic displacements in this situation, and are generally captured as

$$N > F, \tag{5}$$

where F represents distant objects beyond fixation, as in Equation 1. Notice that in this inequality there is no negative sign. Thus, if the observer can recognize lamellar displacements and velocities that are the reciprocal of distance, then this could be information supporting the detection of a collision. This arrangement is suggested in the middle panels of Figures 7 and 8.

Passing Behind

When an observer is passing behind a moving object, his or her gaze-movement angle gets smaller (until the object crosses over his or her path). This eye or head rotation is added to the lamellar pattern of optical flow and makes retinal motions more uniform, decreasing the differences with depth that occur in the other conditions. Thus, motion in the retinal field becomes nearly uniform, yielding nearly null parallactic displacements. These motions are suggested in the right panels of Figures 7 and 8 and are generally captured by the relation

$$N \sim F. \tag{6}$$

The form of this equation is quite different from that of the previous three. There is neither a reversal of motion as in Equations 1 and 4, nor a clear inequality as in Equations 1 and 5.

In Experiment 3, we explored observers' ability to detect collisions and the near-collisions closely related to them. Our investigation of these situations centers on the constancy or change in the gaze-movement angle entailed in this type of situation and implied in Figures 7 and 8. Of course, collisions along curves or under acceleration or deceleration can also occur, but these are not yet pertinent to our research program.

Experiment 3: Detecting Collisions and Near-Collisions With a Pedestrian in a Cluttered Surround

We are interested in an observer's ability to detect his or her potential collision with another moving object approaching from any possible angle. Unfortunately, the literature is devoted almost exclusively to what might be called head-on collisions (e.g., Carel, 1961; Kaiser & Phatak, 1993; Kim, Turvey, & Carello, 1993; Lee, 1980; Savelsbergh et al., 1992; Schiff & Detweiler, 1979; Todd, 1981) and near misses related to them (Kaiser & Mowafy, 1993; Peper et al., 1994; Schiff & Oldak, 1990). That is, if the observer and object can both be said to be moving, they approach each other at an angle of 180°. Because little is known about the detection of collisions between moving objects on non-180° approach paths, and because their geometry is potentially so important and interesting, we concentrate on these.
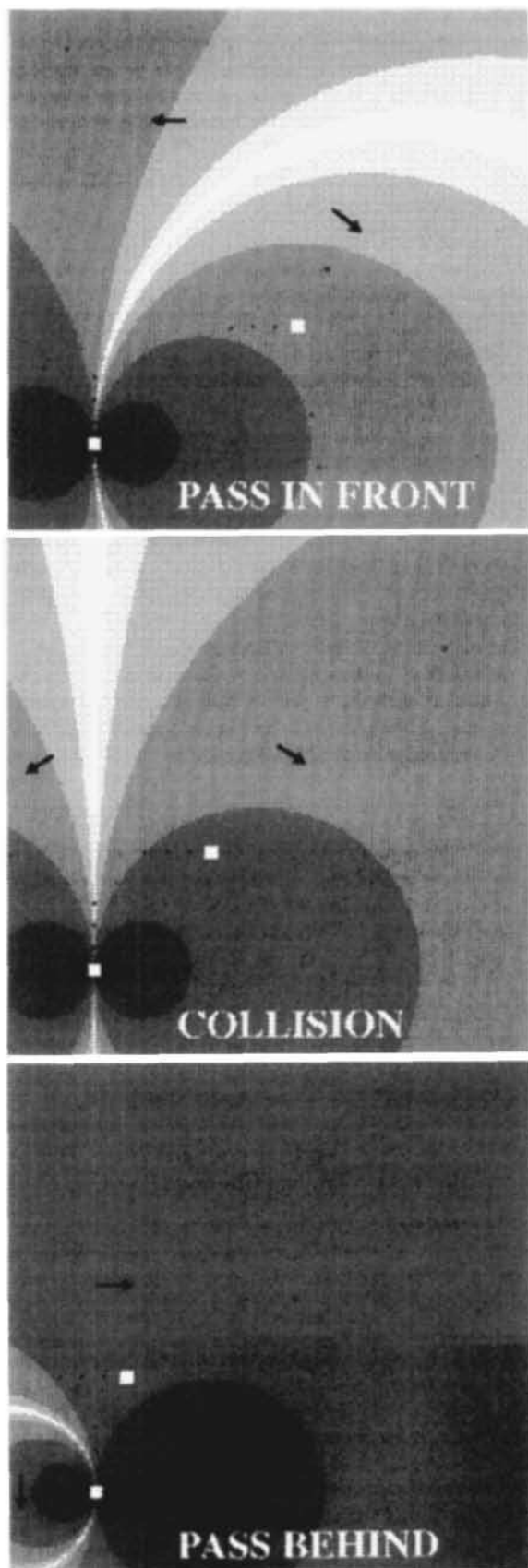
Method

The simulated visual situation is suggested in Figures 9 and 10. In all cases, the paths of the observer and pedestrian, when extended, would meet at what we call the *crossover point.* On one third of all trials the observer and the pedestrian were on a collision course; on one third the pedestrian would pass in front of the observer; and on one third the observer would pass in front of the pedestrian. No actual collisions or bypasses occurred in the visual stimulus sequences; instead, all trials were cut short well before these would occur.

The pedestrian and observer could approach each other from six angles (45, 90, 135, 225, 270, and 315°), as suggested in Figure 9. For noncollisions the bypass time was also varied, as suggested in Figure 10. The difference in the amount of time between the arrival of the pedestrian and the observer at the crossover point will be called *headway.* In this experiment, headways were ± 1.8, 3.6, and 5.4 s, and at this velocity were also equivalent to ±4.05, 8.1, and 12.15 m. Finally, although trial duration was always constant at 7.2 s, the absolute distance from the crossover point of the pedestrian and the observer was varied. That is, for collision trials the motion sequences ended either 3.6, 7.2, or 10.8 s before collision (or 8.1, 16.2, and 24.3 m before they reached the crossover point). For noncollision trials, the sequences also ended when the observer was 8.1, 16.2, or 24.3 m from the crossover point; the pedestrian was at either a lesser distance (when the observer passed behind) or a greater distance (when the observer passed in front) from the crossover point.

Again, the simulated noncollision movements generally combined a dolly and a pan. Mean absolute simulated eye/head rotation rates (the pan component) for noncollision trials across all approaches were 0.84, 1.69, and 2.29°/s, respectively, for the three headway conditions. Collisions, because of their constant gaze-movement angle, entailed no rotations and thus contained only a dolly (with a camera angle fixed at 22.5, 45, or 67.5° with respect to the direction of translation for the 135, 90, and 45° trials, respectively). At the end of the trial, all motion stopped, and the last frame remained on the screen. The Iris mouse was turned sideways, and, after the motion ended on each trial, the observer indi-

Figure 8. A second set of representations of the geometry of retinal displacements for an observer passing in front, colliding with, and passing behind a moving object. These panels are bird's-eye views of the moving observer, always near the bottom left of each panel, indicated by a white square, and the pedestrian, always near the middle of each panel and indicated by the other white square. Here, rather than tracing the history of displacements as in Figure 7, the instantaneous velocity fields are shown for the observer looking at the pedestrian. The small black dots indicate the directions of the observer (always vertical) and pedestrian (always horizontal and to the left). The lightest ring in the surround indicates retinal velocities near zero. Those rings of increasing grayness circling to the right indicate increasing velocities to the right; those rings with increasing grayness circling to the left indicate corresponding velocities to the left. The directions of objects and textures within both areas are suggested by the black arrows. Notice that when the observer is passing in front of a pedestrian there will be retrograde motion along the line of gaze from the observer to the pedestrian that is well behind the pedestrian. This motion is in the same direction as the observer's movement. When on a collision course, the displacement pattern is symmetrically shaped to the left and right of the observer's linear path, characteristic of descriptions of optical flow (without rotational flow). When passing behind the pedestrian, the displacement pattern is nearly uniform in front and behind the observer. The case of collision is exactly as in Figure 7; the cases of passing in front and behind, however, are somewhat more extreme here to show the pattern of displacements around the moving object.
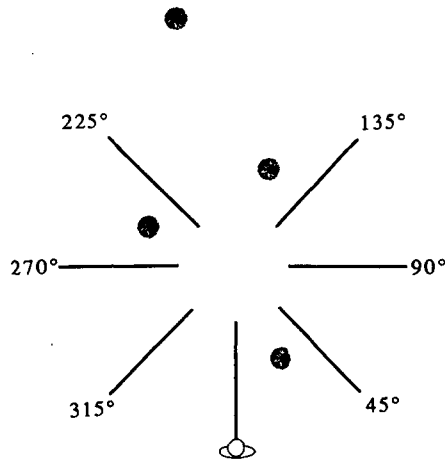
Figure 9. A schematic, overhead view of the six approach paths of the pedestrian in Experiment 3, prior to a possible collision. All paths shown here are for a collision. Note that the 180° approach was not used.

cated whether he or she would go in front of the pedestrian (by pressing the front button), collide with the pedestrian (by pressing the middle button), or go behind the pedestrian (by pressing the rear button).

There were four factors in this experiment: 6 angles of approach of the pedestrian (45, 90, 135, 225, 270, or 315°); 3 absolute distances apart (ending 3.6, 7.2, or 10.2 s before the observer would reach the crossover point); 3 types of observer–pedestrian interaction (collision and the two forms of noncollision—passing in front and passing behind); and, among noncollision trials, 3 headways (1.8, 3.6, or 7.2 s; each type of collision trial was represented 3 times each as well). This yielded a total of 162 trials. Headway was varied across blocks; all other variables were randomly ordered within a block. Eight new observers participated; half viewed the headway blocks in ascending order, and half viewed them in descending order.

Results and Discussion

Bypasses. We first considered only the noncollision trials and cast them in a regression analysis. We coded the responses as 1 for passing in front, 0 for collision, and −1 for passing behind, and we then summed the coded responses across individuals and used this response measure as the dependent variable. The first regression revealed no main effects. Angle of approach, distance, and headway were all nonsignificant, as were a large number of interactions and the order of headway blocks. We felt that this first analysis may not have been the appropriate approach to the data. We then added a new independent variable—the change in the gaze-movement angle during the course of the trial—and reran the analysis with four independent variables. In this regression, the change in gaze-movement angle accounted for more than 66% of the variance in the data, $F(1, 49) = 122.3, p < .0001$. The other main variables—headway, angle of approach, and distance—were now marginally significant, but they accounted for only 2% of the variance each, $3.27 < Fs(1, 49) < 4.37; .04 < ps < .07$. None of the interactions accounted for any significant amount of variance in the noncollision data. Thus, information supporting collision avoidance is in the pattern of retinal displacements generated by the change

or nonchange in the gaze-movement angle during the observer's approach to the crossover point.

Because it is so important, let us consider the statistical issue concerning the relation between change in gaze-movement angle and the other variables in more detail. The reasons that the change in gaze-movement angle absorbed the variance and then created marginally reliable effects in the other variables are severalfold: First, the distance the observer had yet to cover before reaching the crossover point was correlated, across all trials, with absolute change in gaze-movement angle during each trial, $r = -.51, t(61) = 4.67, p < .0001$. Mean absolute changes in gaze-movement angles for noncollision trials were 20.3, 8.2, and 5.4° for the three distances from the crossover point, from close to far. That is, the closer one is to an object, but not on a collision course with it, the more the gaze-movement angle will change. Second, the amount of headway between observer and pedestrian was also correlated with absolute change in gaze-movement angle, $r = -.71, t(61) = 7.95, p < .001$. Mean absolute changes in gaze-movement angles were 5.9, 12.2, and 16.5° for the three headways, from 10.8 to 7.2 to 3.6 s, respectively. Thus, within the constraints of this study, the less time there was between the arrival times of the pedestrian and observer at the crossover point, the larger were the changes in gaze-movement angle. Third, the acuteness of the angle of approach between observer and pedestrian was correlated with absolute change in gaze-movement angle, $r = -.31, t(61) = 2.61, p < .015$. Mean absolute changes in gaze-movement angles were 17.2, 8.8, and 7.0° for acute, perpendicular, and obtuse approaches, respectively. That is, gaze-movement angle during bypasses changed more the more acute the angle between the paths of the observer and the pedestrian.

Collisions. We then considered the collision trials by themselves, scoring them as correct (a collision response) or incorrect (collapsing across the categories of passing in front of and behind). Here, this new regression analysis revealed two effects.
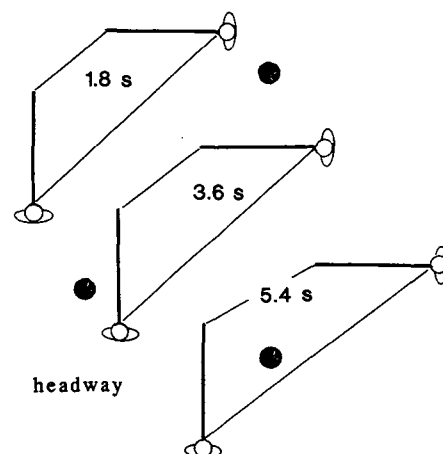

Figure 10. A schematic, overhead view of the three headways (bypasses) used in Experiment 3 where the observer (shown at the bottom) would pass in front of the pedestrian (shown to the right approaching at 90°). One third of all trials entailed collisions, in one third the observer passed in front of the pedestrian as shown here, and in one third the observer passed behind the pedestrian.
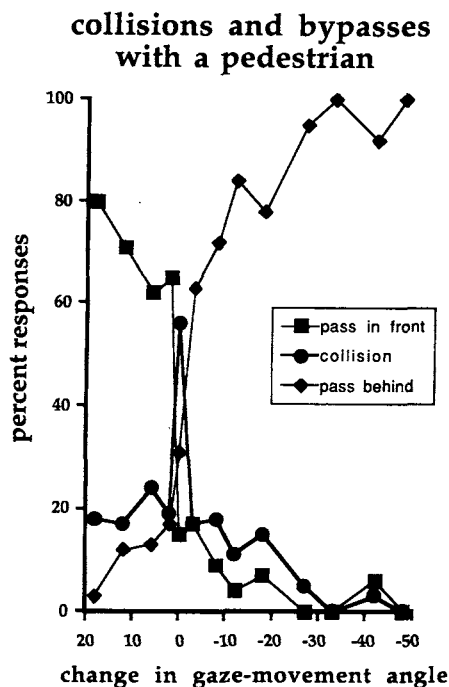
collisions and bypasses with a pedestrian

Figure 11. Results of Experiment 3 plotted as a function of the change in gaze-movement angle during the course of a trial. No change indicates a collision, positive changes indicate an increasing gaze-movement angle and passing in front of the moving pedestrian, and negative changes indicate a decreasing gaze-movement angle and passing behind the pedestrian.

First, there was a reliable effect of angle of approach, $F(1, 24) = 5.15, p < .03$, which accounted for 10% of the variance in the data; performance was 66, 48, and 50% for acute, perpendicular, and obtuse approaches, respectively. Second, there was a reliable effect of distance (and thus time) before the collision, $F(1, 24) = 23.25, p < .001$, which accounted for 44% of the variance; performance was 80, 51, and 39% for increasing amounts of distance (and time) from the crossover point. However, when the absolute distance between observer and pedestrian was used to predict the results, a variable that is correlated with both angle of approach and the experimental variable of distance from crossover, a full 50% of the data was accounted for, $F(1, 25) = 24.75, p < .0001$. In essence, observers seem to have a bias against predicting a collision when it is not imminent, and we return to these results in the general discussion. Finally, there could be no effect of the change in gaze-movement angle for collisions because its value was always zero for these trials.

Overall results for collisions and bypasses are plotted in Figure 11 as a function of the change in gaze-movement angle, with trials collapsed within bins of 5° for collisions (± 2.5°) and near-collisions and within bins of 10° for changes in gaze-movement angle greater than 12.5°. As suggested in Figure 12, positive changes in gaze-movement angle (increases in the gaze-movement angle during the trial) occur when the observer is going to pass in front of the pedestrian; negative changes occur when the

observer is going to pass behind; and no change, as outlined above and as shown in Figure 6, entails a collision.

Notice that, given the geometry of these settings (suggested in Figures 9 and 10), there is an asymmetry that occurs in the two bypass conditions: Absolute change in gaze-movement angle is considerably greater for situations in which the observer passes behind a moving object than when the observer passes in front, even though bypass times are the same. Notice further that performance is generally symmetric with the change in gaze-movement angle and would not be if plotted according to bypass time.

Finally, we devised a measure sensitive to the change in gaze-movement angle for the accuracy of collision detection. We took the collision function shown in Figure 11, assumed it was normally distributed, and computed its standard deviation. The overall standard deviation across all bypass conditions was 11.5° of change in gaze-movement angle; but the standard deviations for the separate bypass conditions were 7.0, 7.6, and 11.2°, respectively, for 1.8-, 3.6-, and 5.8-s bypasses. The value for the 3.6-s condition will be useful for comparison with later studies.

Where Is the Information for Collisions and Bypasses Located?

We think the results of Experiment 3 are convincing in demonstrating that the change in the gaze-movement angle during the course of the trial accounts for most of the variance in the data. However, from the results of Experiment 3 alone we do not know the locus of this information that supports the use of changes in gaze-movement angle, nor do we know its form. Four complimentary sources suggest themselves.

Monitoring Eye Movements

First, and perhaps most obvious in the natural situation, the gaze-movement angle is typically associated with eye rotations or head rotations. Muscular feedback from these motions is likely to provide a source of information for collisions and bypasses, because it appears to play some role in wayfinding (Royden et al., 1992). However, because our displays nullify
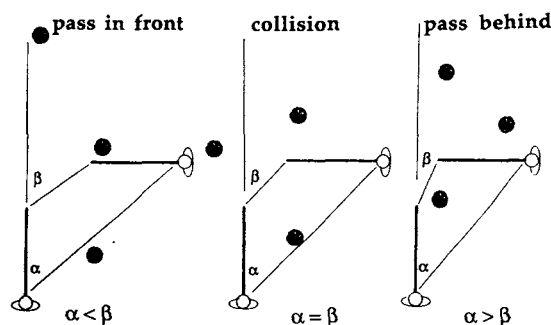

Figure 12. The change or nonchange in gaze-movement angles for the three situations of approach to a pedestrian at right angles. This angle increases when the observer passes in front, stays the same for an imminent collision, and decreases when the observer passes behind, regardless of the angle of approach.

this information by simulating the pursuit fixation while maintaining a fixed gaze at midscreen, this source can play no role here. Thus, in essence, we are searching for the adequacy of optical information; the relative role of information from muscular feedback can be determined at a later date.

Monitoring the Aimpoint

Second, perhaps the aimpoint is detected and the angular extent between the gaze and aimpoint monitored. Experiment 2 demonstrated that in our situation aimpoint is not known by the observer, but one might contend that this is a possibility in real life. However, Crowell and Banks (1993) showed that aimpoint detection is considerably impaired 10 and 40° into the periphery compared with that in the fovea; and trials here presented gaze-movement angles of 22.5, 45, and 67.5°. Thus, at these angles one's heading would appear generally unavailable to a moving observer even in the real world.

Monitoring Object Orientation

Third, perhaps the observer detects a change in orientation of the pedestrian. The change in gaze-movement angle is identical to the amount of relative rotation the pedestrian undergoes during the course of the trial. That is, during a collision approach, the pedestrian undergoes no rotation with respect to the observer but simply looms larger and larger until contact. When the observer passes in front, however, the pedestrian looms larger but also rotates toward the observer, revealing more and more of his front side. In contrast, when the observer passes behind, the pedestrian looms larger but rotates away from the observer, revealing more and more of his back side. The direction and amount of rotation could serve as a source of information about collisions and noncollision.

Monitoring Motions Around Fixation

Fourth, perhaps the observer monitors the relative motions of objects and textures in the foreground and background. This, of course, is the scheme we proposed when discussing Figures 7 and 8. The change in gaze-movement angle is also identical to the amount of rotation of the ground plane (trees and grid) around the pedestrian. That is, any increase in the gaze-movement angle when the observer is looking to the right and passing in front of the pedestrian is identical to the amount of counterclockwise rotation in the ground plane. Similarly, any decrease in the gaze-movement angle when the observer is looking right and passing behind the pedestrian is identical to the amount of clockwise rotation. (When the observer is looking left, these rotations continue to be identical but are reversed in direction.)

The latter two hypotheses contrast in their consideration of what rotates in the visual field—the object or the clutter in the foreground and background. Experiments 4 through 6 provide various tests of these two hypotheses. In Experiment 4, we manipulated object information. We replaced the pedestrian with an upright cylinder of the same size and color and effectively removed all possible object-rotation information. In Experiment 5, we studied the effect of foreground and background information, presenting the pedestrian but removing the back-

ground trees and the grid. Experiment 6 was a further control, and we presented the cylinder (without object-rotation information) but again without any foreground and background information.

Experiment 4: Detecting Collisions and Near-Collisions With an Upright, Moving Cylinder in a Cluttered Surround

Method

Two types of stimulus sequences were used in this study. The first was identical in methodological detail to the ± 3.6-s headway condition in Experiment 3 and hence constitutes a partial replication (R) of that study. The second, experimental (E) sequence was the same except that an upright, yellow cylinder was substituted for the pedestrian. The cylinder subtended the same vertical visual angle as did the pedestrian, and its radius was slightly greater than the pedestrian's torso. Each of the four sequences had 54 trials: 6 angles of approach (45, 90, 135, 225, 270, or 315°) × 3 absolute distances apart (ending 3.6, 7.2, or 10.8 s before collision or crossover) × 3 object interactions (collision and the two forms of noncollision). Six naive observers participated. Each viewed four sequences; half viewed them in the order REER and half in the order ERRE.

Results and Discussion

There were no reliable effects of group or order, nor was there a reliable interaction between them, Fs < 1.0. Moreover, there was no significant difference in performance between the two types of stimuli—75% for trials simulating forward movement with gaze on the pedestrian and 76% for trials simulating forward movement with gaze on the cylinder. The overall pattern of responses is shown in Figure 13. Using the scheme from our analysis of the results in Experiment 3, we then coded the three categories of response—1 for the observer passing in front, 0 for a collision, and −1 for the observer passing behind—and then summed responses for each of the 27 stimulus types (3 angles of approach × 3 distances apart × 3 pedestrian–observer interactions) in the two conditions across observers. The correlation between results on the two tasks was very high, r = .969, p < .001. As shown in Table 1, the standard deviations for the two collision-response functions were 7.3° of change in the gaze-movement angle for the replication sequence and 6.7° of change for that with the upright moving cylinders. Thus, it is quite clear that removing the three-dimensional rotational structure of the pedestrian had no negative effect on observers' responses or overall accuracy. Such results suggest that foreground and background motions are necessary and sufficient for the task. In the next two experiments, we manipulated the presence of the trees and grid to test further their necessity.

Experiment 5: Detecting Collisions and Near-Collisions With a Pedestrian in a Clutterless Surround

Method

Again, two types of stimulus sequences were used in this study. The first was identical in methodological detail to the replication sequences used in Experiment 4 (and the ± 3.6-s headway condition of Experiment 3) with the pedestrian. The second was the same except that fore-
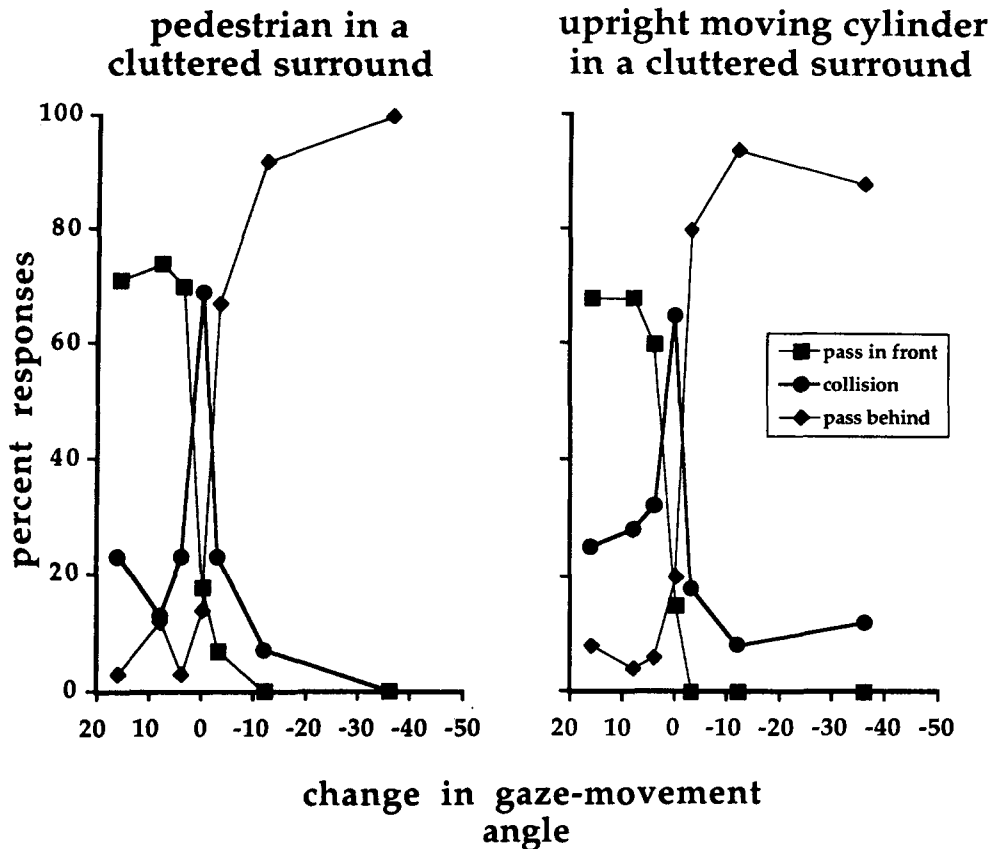
Figure 13. Results of Experiment 4. The left panel shows the partial replication of the results of Experiment 3, in which the observer looked at a moving pedestrian, composed of yellow rectangular solids outlined in red, walking through an environment with trees and a grid on the groundplane; the right panel shows results for an upright cylinder moving exactly like the pedestrian in the same environment. In the second case, there were no internal markings on the object, so the observer could not know in which direction it was rotating. Performance was undiminished.

ground and background information—the grid and all trees—were removed from the display. Six observers participated, 4 of whom had participated in a previous study and 2 of whom were naive. Viewing orders of sequences were the same as in Experiment 4.

Results and Discussion

Again, there were no reliable effects of group or order, nor was there a reliable interaction between them, Fs < 1.0. However, there was now a significant difference in performance on the two types of stimuli, $F(1, 5) = 81.8$, $MSE = 31.1$, $p < .001$, as suggested in Figure 14. Overall, observers were 77% correct on the replication sequence, but only 50% correct when the trees and grid were removed. Chance performance, remember, is 33%. Collapsing responses into category codes as before, we found that the correlation between responses in the two conditions was reliable, $r = .82$, $p < .001$, but also reliably weaker than, and not nearly as compelling as, the correlations in Experiment 4, $t(24) = 3.18$, $p < .005$. Moreover, as shown in Table 1, the standard deviations for the two collision-response functions were 6.6° of change in the gaze-movement angle for the replication sequence and 11.3° of change for that without trees

or grid. Because performance in the clutterless condition was above chance and because responses were not distributed uniformly across the changes in gaze-movement angle, some residual information about collisions and bypasses is available in object rotation. However, because performance was markedly worse in this condition, it is also doubtful that such information is sufficient for the task. Moreover, Experiment 4 showed that it is not necessary. In our later discussion we consider the pragmatic needs in the detection of collisions.

Experiment 6: Can One Discriminate Collisions From Bypasses With a Featureless Object in a Clutterless Surround?

The final experiment in this interim series served as an ultimate control for detecting rotations of any kind as they might serve collision detection. We also conducted it to serve as a clarion to others interested in collision research but who have neither considered the difference between judgments of collisions and bypasses in situations other than 180° approaches nor questioned their assumptions about ϕ or θ in Equations 2 and 3.

Table 1

Standard Deviations of Collision-Response Functions for Relevant Conditions in Experiments 3 Through 7 (in Degrees of Change in Gaze-Movement Angle)

Study	Control condition[a]	Experimental condition	Experimental manipulation
Experiment 3	7.6		
Experiment 4	7.3	6.7	Moving cylinder with environmental clutter
Experiment 5	6.6	11.3	Moving pedestrian without environmental clutter
Experiment 6	6.6[b]	15.8	Moving cylinder without environmental clutter
Experiment 7		0.5	Stationary tree with environmental clutter

[a] The control condition in each experiment consisted of trials mimicking observer translation while looking at a moving pedestrian, both traversing a sparse forest over a randomly oriented grid.   [b] The same observers participated in Experiments 5 and 6, and the values for the control conditions are based on the same data (those for Experiment 5).

Method

Only one stimulus sequence of 54 randomly ordered trials was used in this study. Here only the cylinder was presented; there was no ground grid and there were no trees. Thus, although the sequence of each trial followed the same layout geometry of the previous studies, only an enlarging cylinder could be seen in the displays. The same 6 observers participated here as in Experiment 4, immediately after completing that experiment.

Results and Discussion

As expected, observers simply could not perform the task. Overall performance was 33%, exactly at chance. On 73% of all trials the observers said that a collision would occur, on 5% they gave pass-in-front responses, and on 22% they gave pass-behind responses. These proportions simply represent a bias; they did not vary when there was a true collision or one of the two bypass possibilities. Because these observers also participated in Experiment 4, one can compare the coded results (1 = *pass in front*, 0 = *collision*, −1 = *pass behind*) here with those of the two conditions in that experiment. Both showed no reliable trend, $rs < .18$, $ps > .35$. Moreover, as shown in Table 1, the standard deviation for the collision function was as large as it could be in this context—15.8° of change in the gaze-movement angle.

Although these results may at first seem trivial, we think they are not. They serve two purposes. First, they demonstrate a true floor effect against which the results of Experiment 5 can be compared. That is, there is indeed *some* information for collisions and bypasses in object rotation, even though that information is not nearly as potent as the rotations of the surround and probably not sufficient. Second, if one accepts the constraints of generalizing from our pursuit-fixation displays, these results suggest that the expanding image of an object may not be sufficient for judging whether or not a collision will occur; tau in whatever form and however relevant to the timing of collisions seems to have no value that can help the observer predict whether or not a collision is imminent in our situation. Thus,

we suggest that studies not considering the relative motion of foregrounds and backgrounds and yet still measuring observer sensitivity to time-to-contact must assume that the observer already knows that a collision will occur. Without foreground and background context or without knowledge of heading, there is no such information in the visual array.

Experiment 7: On the Accuracy in Judging Collisions With a Stationary Object

Experiments 3 through 6 were all concerned with the detecting of collisions and bypasses with moving objects. Moreover, in each we measured the relative accuracy (in standard deviations of the change in gaze-movement angle) of detecting a collision. In each case, this was possible because of the nature of the task, which was a three-alternative forced-choice procedure. Looking back at Experiment 1, which like our previous studies (Cutting et al., 1992; Vishton & Cutting, 1995; but see Cutting, 1986) used a two-alternative forced-choice procedure, we cannot reconstruct the relative accuracy in detecting collisions. Thus, Experiment 7 is a replication of the setting of Experiment 1, with an observer looking at a stationary object (tree) during pursuit fixation while strolling through a sparse forest, but with three alternatives—passing left, collision, and passing right.

Method

Six naive observers participated. They observed a random sequence of 140 trials: 7 gaze-movement angles (0.0, 0.5, 1, 2, 4, 8, and 16°) × 2 gaze directions (left and right, and with the 0.0° trials doubled in occurrence) × 10 replications. Because we wish to compare the results here with those of Experiments 3 through 6, we must consider the changes in gaze-movement angle at each nonzero gaze-movement angle. These were half the value of the gaze-movement angles—0.25, 0.5, 1, 2, 4, and 8°, respectively—but were always positive in value (i.e., with the simulated gaze diverging from the path of movement). Observers pressed the left button of the Iris mouse if they believed they were going to the left of their gaze, the right button if they believed they were going right, and the center button if they thought a collision with the fixation tree was imminent. In all other respects, sequences were identical to those in Experiment 1, but without the roving pedestrian wandering through.

Results and Discussion

Bypasses. Let us first ignore collision responses and the 0° gaze-movement angle stimuli. Looking only at the changes in correct performance on the other gaze-movement angles, we found again a reliable effect, $F(5, 25) = 52.7$, $MSE = 139.5$, $p < .001$, that replicated previous results. Moreover, even with a three-response task, 4 of the 6 observers met the 95% criterion at the final gaze-movement angle value nearest 3.3°. Beyond this result, there was no effect of gaze direction (left vs. right) nor was there an interaction between gaze direction and gaze-movement angle, $Fs < 1.0$.

Collisions. Of course, the more interesting data in this context are in the collision responses and their relation to those in the other experiments. These data are shown in Figure 15 as a function of the change in gaze-movement angle. Rather than being measured in terms of positive and negative changes in gaze-movement angle, as they were for the data of Figures 10
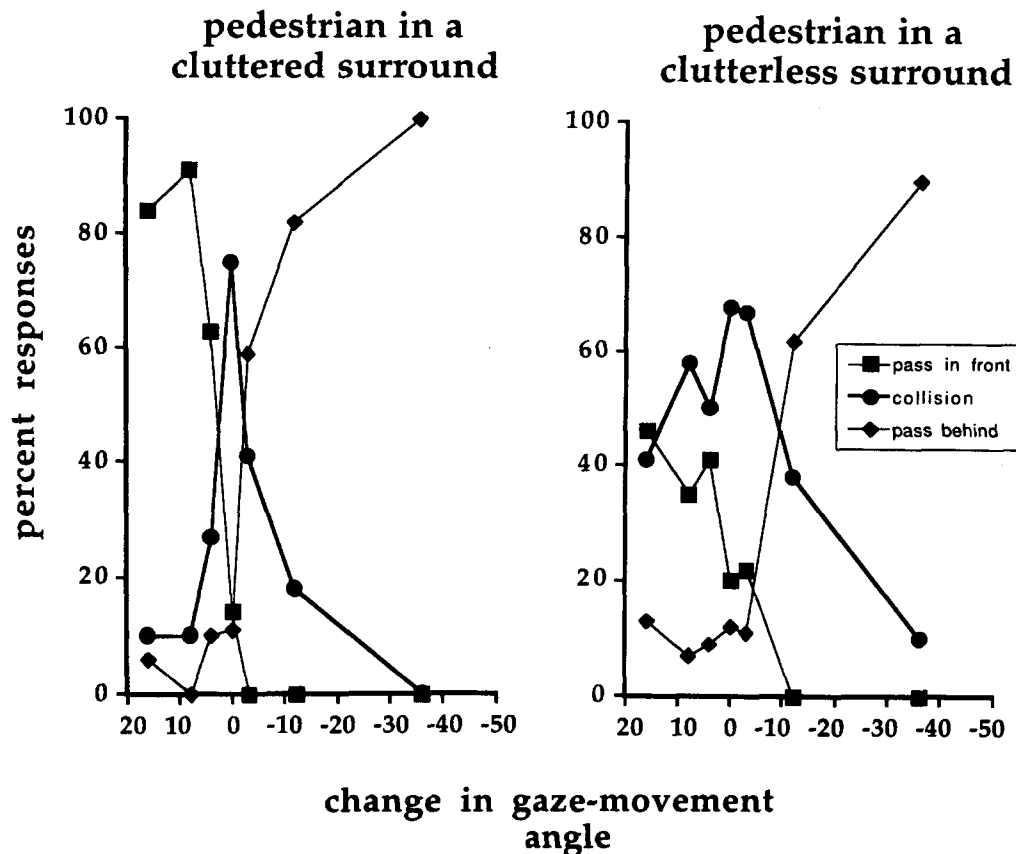
pedestrian in a cluttered surround

pedestrian in a clutterless surround

change in gaze-movement angle

Figure 14. Results of Experiment 5. The left panel shows the partial replication of the results of Experiment 3, in which the observer looked at a moving pedestrian with trees and grid in the foreground and background; the right panel shows the results for the same pedestrian but without any environmental clutter. In the second case, performance was considerably worse than in the first. These results, taken together with those shown in Figure 13, suggest that environmental rotations are considerably more important than object rotations in observers' performance on judging collisions.

and 11, these are measured in terms of changes in gaze-movement angle to the left and to the right (again, all changes in gaze-movement angle for observers looking at stationary objects along linear paths will necessarily be positive). Most critically, as shown in Table 1, the standard deviation of the collision-response function was only 0.47°, more than an order of magnitude smaller than those of Experiments 3 through 6. We take this as possible evidence that wayfinding and collision detection in the case of looking at a stationary object are considerably superior to collision detection in the case of looking at a moving object. Nonetheless, because we do not yet know the demands of the second task, we cannot yet assess the adequacy of our results. Those are addressed later in the discussion.

Empirical Conclusions

On the basis of the results of the seven experiments presented here we can conclude several things. First, as reported by Cutting et al. (1992; Cutting, 1986), the retinal displacement information from looking at stationary objects in one's surround during locomotion is adequate to yield information both about

guiding one's path through it and about avoiding collisions with those objects. We think this particular information is in differential parallactic displacements (near objects moving farther than and in the opposite direction from far objects) and related sources (Cutting et al., 1992; Vishton & Cutting, 1995). In principle, however, we have no way of distinguishing this information in these studies from more standard decompositional approaches (e.g., Warren & Hannon, 1990; Warren et al., 1988) in which the rotational flow field that is due to eye movements is subtracted from the translational field that is due to the observer's forward movement. That evidence was presented by Cutting et al. (1992).

Second, these displacements on the retina are not generally adequate for detecting one's direction of motion when looking at a moving object in the environment, at least under the conditions of simulated fixation studied here. The only exception is when one is looking at an object coming almost directly at one along a parallel path. Thus, the purpose of looking at a moving object during locomotion seems not to be to gather further information about one's aimpoint. Instead, it must be to gather information to avoid collisions with that object. Moreover, in
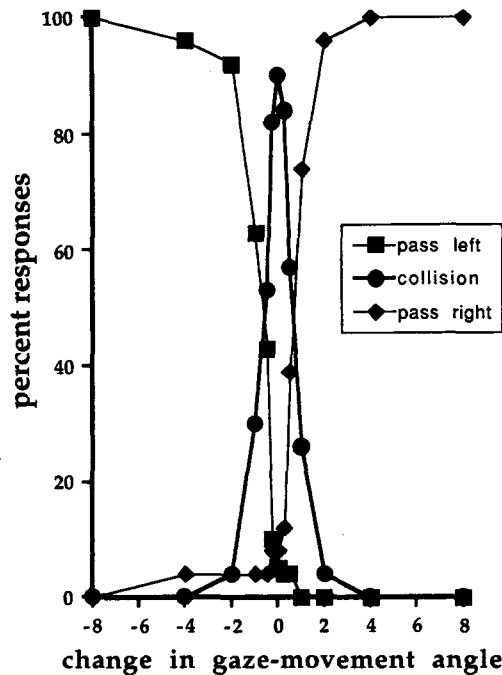
tree in a cluttered surround

Figure 15. Results of Experiment 7, for three-category judgments of collisions and near-collisions with a stationary object. These data are to be contrasted with those in Figure 11 for Experiment 3 and those for the replication conditions in Figures 13 and 14 for Experiments 4 and 5. Note the change in the scale of the abscissa.

such situations it appears that one cannot generally gather information about one's aimpoint and a potential collision at the same time. This combination of results is somewhat embarrassing for decompositional approaches to wayfinding: If decomposition were to occur in this situation, the translational field would yield the aimpoint. If human observers engaged in such a process, they would then surely be able to judge both aimpoint and whether or not a collision was imminent.

Third, judgments of collisions and bypasses with moving objects during pursuit fixation can be made on the basis of information supporting nonchanges and changes in gaze-movement angle, respectively. One need not first compute the paths of movement for oneself and the object under scrutiny. Thus, the various forms of tau information cannot be relevant to this task. The locus of collision and noncollision information is in the relative motions of foreground and background objects and textures as one engages in pursuit fixation of the moving object.

Fourth, the absolute accuracy in judging a collision with a stationary object appears to be an order of magnitude better than that of judgments of collision with a moving object, at least when measured by the same parameter. The standard deviation of the former is about 0.5° measured in terms of the change in gaze-movement angle, whereas the standard deviation for the latter is near a 7.0° change in the gaze-movement angle.

Three threads remain to be spun and then wound into the

fabric of our argument. First, how accurate must one be in avoiding collisions and satisfactorily predicting bypasses? Second, what is the relation between the collision information we have discovered and tau? And third, what do these results imply about directed perception, and vice versa?

Task Adequacy

Collisions With Stationary Objects

In the case of wayfinding and avoiding possible collisions with a stationary object, Cutting et al. (1992) and Vishton and Cutting (1995) suggested that a pedestrian moving at about 2.25 m/s must know where he or she is going with 95% accuracy within 3.33° of visual angle. Increases in observer velocity entail increases in needed accuracy; decreases in velocity entail decreases. For standard gait, however, the results of Experiment 7 suggest that the 95% criterion at 3.33° corresponds to collision judgments with a standard deviation of less than about 0.5° of visual angle. This means that collisions will be detected with 95% accuracy within ± 1° of change in the gaze-movement angle. Under most conditions we have tested in the laboratory, most observers are able to meet this criterion; in the real world, we think virtually everyone can, and must, meet it.

Collisions With Moving Objects

Is a standard deviation of about 7° of change in the gaze-movement angle adequate for avoiding a moving object? In the case of such collisions, the calculations have not yet been made. Thus, in this section, we provide some tentative criteria. Before beginning, however, we need to make a number of assumptions.

First, we assume, as in these experiments, that the observer and the pedestrian are moving with the same velocity, at 2.25 m/s. Second, we assume each is roughly equivalent to a vertically oriented cylinder. This second assumption temporarily rules out certain considerations of traveling in, or being worried about colliding with, elongated moving objects such as trains and even automobiles. The notion of bypassing such a vehicle by going behind it, or passing in front of another when in such a vehicle, must be modified from what we present here. Third, for simplicity's sake we start with collisions at 90° and then generalize to oblique collisions at both acute and obtuse angles. Such layouts are suggested in Figure 16.

Necessary accuracy and the detection of safe bypasses. In an approach to a crossover point with a moving object there are two windows to avoid—a distance window and a time window—that are reciprocally measured with respect to a given velocity. If we assume a pedestrian has a radius of about 0.5 m (with arms and legs extended), then for 90 and 270° approaches there is a distance window of about ± 1.2 m around the crossover point which the observer must avoid. That is, the observer would collide with the pedestrian if they both approached the crossover point within this span. At 2.25 m/s this distance window corresponds to a temporal window of about ± 0.5 s. For more acute and obtuse approaches both windows are slightly smaller.

Let us continue to work backward from the crossover point. From the general calculations of Cutting et al. (1992, Table 1)

0.53 s window to avoid

at 2.25 m/s
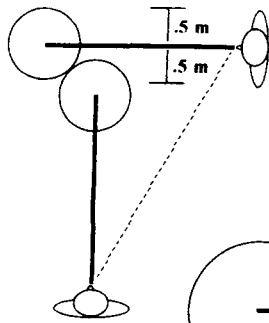
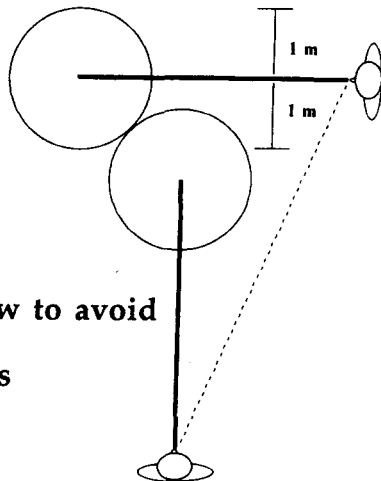## 1.06 s window to avoid

at 2.25 m/s

Figure 16. Some geometric constructions for calculating the necessary accuracy of a moving observer avoiding an object moving at the same velocity. The upper panels show a situation depicting the needs under conditions of absolute accuracy; the bottom panels show the same situation but allow for a buffer zone between observer and pedestrian. Both show bypasses, with the moving observer passing just behind the pedestrian. If the panels were rotated 90° and then flipped around the vertical axis, the situation for the observer passing in front would be shown.

and for a gait of 2.25 m/s, a readied observer may need as much as 2 m to negotiate a turn (including both footfall modulation and the turn itself). In addition, Cutting et al. (1992) and Vishton and Cutting (1995) demonstrated that at least 3 s of stimulus sequence is typically necessary to register the information for an observer to find his or her way with 95% accuracy at the appropriate gaze-movement angle. If we assume this interval (3 s) is also needed for the collision detection task (an assumption untested so far, but not out of line with estimates from the Road Research Laboratory, 1963, and Probst et al., 1984), then the observer needs to move an additional 6.75 m back from the crossover point, for a total distance of 8.75 m from it.

Consider next the following situation: The observer is 8.75 m from the crossover point and moving at 2.25 m/s, and the pedestrian approaches at 90° at the same velocity with a headway of 1.2 m (and thus is 7.55 m from the crossover point). This pedestrian will just pass in front of the observer without collision and without the need of footfall adjustments on the part of either. With the observer fixated on the pedestrian and

during the next 3 s (6.75 m) there will be a −19° change in the gaze-movement angle. Similarly, when the observer has a headway of 1.2 m, allowing him or her to just pass in front of the pedestrian, the change in gaze-movement angle during the same interval would be 9°. Again, notice the asymmetry in changes in gaze-movement angle for the two classes of bypass.

The problem with the calculations above for absolute collision detection is that it allows for no margin of safety. Moreover, there is an element of personal space that should also be considered. That is, although one may feel unabashed when brushing by a tree with little leeway, one is less likely to infringe on the personal space of another pedestrian unless crowding makes it absolutely necessary. Thus, rather than considering individuals as 0.5-m vertical cylinders, we should consider them (and ourselves) to be surrounded by a buffer zone that other individuals also wish to avoid encroaching upon (see also Gibson, 1961; Gibson & Crooks, 1938). Provisionally, we suggest a buffer zone of an additional 0.5 m, which would make the cylinder effectively 1.0 m in radius. We fully recognize that this estimate will vary by circumstance and by culture, as suggested, for example, by Hall (1966). With this additional assumption the two windows to avoid are doubled in size: ± 2.4 m and ± 1.06 s. A pedestrian approaching at 90° with 3.6 m of headway will create a change in the observer's gaze-movement angle of −47° (the pedestrian will, in fact, have already begun to pass the crossover point); and when the observer has 2.4 m of headway, the change in gaze-movement angle will be 15°. Notice that the asymmetry in the change in gaze-movement angle for the two bypasses is even greater in this case.

Empirical evidence for adequate detection of safe bypasses. All of the trials in Experiments 3 through 6 ended before any turn of avoidance needed to be negotiated. Only in Experiment 3 was there a condition moderately close to our 2-m calculation, and then the trials ended when the observer was 8.1 m from the crossover point. The difference between experiment and requirement suggests that at least 6 to 8 more full steps could be taken before the observer need turn or stop. Nonetheless, some empirical estimates of observer accuracy can be made. The data of Experiment 3 suggest a reasonably high level of accuracy (80%) with changes in gaze-movement angle approaching −20°; and for final distances relatively close to the crossover point (8.1 m), this performance is considerably higher (94%). Only two changes in gaze-movement angle in Experiment 3 exceeded −45°, and performance on both of these was 100%. Thus, regardless of whether one considers the margin of safety or not, people are extremely accurate in our laboratory simulations at detecting safe bypasses when they pass behind the moving object.

However, observers are less accurate in our simulations when they themselves are to pass in front of the moving object. Correct performance for changes in gaze-movement angle of 10 to 15° was only 65%, and changes of this magnitude occurred on only a few trials with a distance of 8.1 m from the crossover point. It may be too conservative to extrapolate from relatively poor performance at such a distance (8.1 m) and to then anticipate poor performance at a point when action must be taken by the observer (at 2 m). Nonetheless, these data suggest that trying to pass in front of a moving object may be more dangerous and more judgmentally flawed than trying to pass behind it.
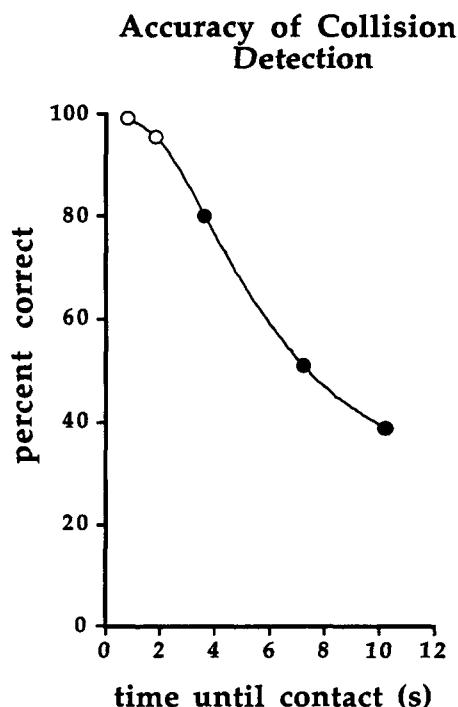
Accuracy of Collision Detection

Figure 17. A logistics function fit to the collision detection data of Experiment 3 (closed circles) as a function of time to contact. These data are used to estimate two points of accuracy for collision detection. The estimated point of 95% performance occurs at 1.9 s and 4.4 m for the conditions studied; that for 99% performance occurs at 0.9 s and 2 m. These estimated points are indicated by open circles.

This situation is all the more grave when one considers that, when driving a car or truck, considerably more of one's vehicle is behind the point of observation than in front of it. The major problem with this form of estimating accuracy is that it considers only bypasses; it does not yet consider collisions.

Empirical evidence for detection of collisions. To assess the experimental adequacy, we selected the collision detection data from Experiment 3, which varied by the ending distance of the observer from the crossover point (8.1, 16.2, and 21.4 m). At a velocity of 2.25 m/s, these collisions would occur in 3.6, 7.2, and 10.2 s. Mean accuracy across the 8 observers for these distances was 80, 51, and 39%, respectively. The three distances were then log-scaled, and a logistic curve was fit to the performance data for each. Cutting et al. (1992) suggested a 95% criterion for wayfinding judgments; if this criterion should be applied to collision detection, the extrapolation of the curve in Figure 17 suggests 95% performance would occur at 1.9 s (or about 4.4 m) from crossover.[5]

Because our calculations above suggested that only 2 m (and probably much less) may be necessary to change direction or come to a full stop, our observers in Experiment 3 easily met this criterion, at least given our measurement assumptions. Indeed, extrapolating further from the function in Figure 17, at 2 m their performance would be about 99%. Thus, given our assumptions (many of which are empirical but as yet untested), we think our calculations show that our collision detection re-

sults are adequate to the naturalistic demands of the task, at least in the context of detecting collisions and when the observer is passing behind a moving object. Moreover, the comparison of the standard deviation of the change in gaze-movement angle for the tasks of avoiding stationary and moving obstacles appears to be a somewhat misleading statistic—observers perform both tasks with accuracies compatible with naturalistic demands.

On Using a Sequence of Information About Collisions

The effective use of information about collisions would seem to entail a two-step sequence: First, and this is the topic of this article, it must be determined whether or not a collision will occur; then, second, if that collision is useful (such as for a feeding gannet or in American football for a free safety tackling a receiver), it must be timed. Various results support such a sequence. In cluttered surrounds, the research we have presented (see Experiment 3) suggests that observers can begin to make reasonable estimates about collision occurrence with at least 10 s to go before possible contact. The research presented by others (Caird & Hancock, 1994; Schiff & Detweiler, 1979; Schiff & Oldak, 1990) suggests that the perception of the time of collision at such a point is often quite inaccurate; only when there is very little time before contact does tau seem to provide accurate information (Savelsbergh et al., 1992). Interestingly, the locus of these two sources of information appears to be different. For collision detection the information cannot be found in the moving object itself, but in its relation to the static objects around it; for timing the collision, on the other hand, the information is in the change in the relative size of the object, and not in what happens to surround the object.

The following scheme emerges: If a moving observer and a moving object are on linear paths moving at constant velocities, if each looms larger to the other, and if there is a constant angle between gaze and movement for both, a collision will occur. For terrestrial situations, the information for detecting the collision appears to be in the relative displacements of objects in front of and behind the moving object as one fixates on it, but not in the growth in retinal size of the object. Performance on our laboratory simulations of this situation is adequate when compared with performance on the real-world task provided that there are sufficient background and foreground textures and objects in the field of view.[6]

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[5] We recognize that fitting a logistics curve to three points is brazen in its trust of the data, but our analyses may be an underestimate of performance. Consider the experiments necessary to achieve a better estimate of the time (and distance) from crossover, and then imagine a trial that ended 0.5 s before collision. For a pedestrian approach of 90 or 270°, that pedestrian would then subtend nearly 45° of visual angle. Given that the Iris display seen from the observer's point of view subtends only 20° of visual angle measured vertically, the image of the pedestrian would overrun the bounds of the display scope. In conjunction with any available rotation information, this event would surely yield greater than 95% performance.

[6] This is true despite the fact that our empirical data suggest that the absolute ability in detecting collisions with a stationary object is an order of magnitude better than that for detecting collisions with moving objects.

If the moving observer wishes the collision to occur, then after the lamellar field is established, the time of collision can be determined by monitoring the expansion of the object (Lee, 1980; Savelsbergh et al., 1992); if the observer wishes to avoid the collision, then there is adequate time remaining for an avoidance maneuver. Bypasses can also be predicted on the basis of visual information. If a moving observer is to pass behind the moving object, the gaze-movement angle will diminish. The information for detecting such a decrease appears to be in the relatively uniform displacement of objects regardless of depth. Performance on our laboratory simulations mimicking this situation also appears adequate to the task, but again only given the presence of background and foreground clutter. If a moving observer is to pass in front of the moving object, then the gaze-movement angle will increase. The information for detecting such increase appears to be in the retrograde displacements (backward from all other motion and in the general direction of observer movement) of objects in the background. However, observers appear to be less adept at picking up this information, and their performance may not be adequate to the task, at least according to our assumptions and analyses.

Overview as a Decision Tree

Finally, we propose a logical decision tree for determining the four cases we began with—collision and noncollision with a stationary or moving object. The same source of information is used throughout, but different forms of that information are used in different circumstances. This tree is outlined in Table 2 and is valid only under certain conditions. First, the visible environment must be rigid in layout or instantaneously a reasonable approximation thereof. Thus, with some care it should be equally applicable to sailing and flight as well as to land travel—although in the former two cases the measurement changes in gaze-movement angle may have to be achieved by means other than the visual registration of differential parallactic displacements. Second, one must be fixated on the object with which one might collide. Under conditions where one is looking elsewhere, this scheme must rely on an orienting mechanism to bring the potential object into the fovea. Third, it seems likely that the local environment should not contain a plethora of other moving objects, although this is an empirical issue whose constraints are yet to be determined.

The first decision to be made is whether or not the fixated object is attached to the rigid environment. Although possible, it seems unlikely that this information is revealed by motion information alone, say, through dynamic occlusion and disocclusion (or accretion and deletion of texture or form; see Kaplan, 1969; Yonas, Craton, & Thompson, 1987). Object identity may have to be determined first, and familiarity with objects that can move or must remain stationary seems likely to play a reasonably important role. If motion alone is used, there is an interesting and serious computational problem (see, e.g., Van den Berg, 1992) to be solved concerning the segregation of occlusions that are due to observer translation from those that are due to object movement. Moreover, when only motion is available, observers seem to be affected in their aimpoint estimations by this object motion (Warren & Saunders, 1995). In our task and with our methods, there is no interaction of object

motion with observer-generated motion, and thus we suggest that this decision is prior to others.

If the object is rigidly connected to the environment, then the presence or absence of differential parallactic displacements will serve to predict bypasses and collisions, respectively. If the object is not rigidly connected to the environment, then, as outlined above. The relative velocities of textures and objects in the foreground and background will predict whether a collision or a noncollision will occur. Notice that the same source of information—the relative displacements of objects around the fixated object—can serve in all four situations; these displacements predict the collision or noncollision with stationary or moving objects.

We expect these analyses will generalize to other similar situations—for pedestrians detecting potential collisions with cars and other vehicles, for drivers of these cars and other vehicles detecting potential collisions with pedestrians, and for drivers detecting potential collisions with other vehicles. If so, such information could be useful for traffic safety instruction and education.

Implications of These Results for Directed Perception and Vice Versa

Directed perception suggests that in any given perceptual situation, particularly those associated with the natural environment, there are multiple sources of information available for the perception of any given object or event and that each of these can specify what is to be perceived (Cutting, 1986, 1991a, 1991b; see also Cutting & Vishton, 1995). The key here is that for any given perceptual task, there may be multiple ways of achieving a solution because there are typically multiple information bases on which one might rely. Sometimes several sources may be combined and used jointly; sometimes one source may be selected. It is the task of the perceptual scientist to try to discover what, when, and why particular sources of information are used.

A corollary of this metatheoretical stance is that in similar situations, such as when considering possible collisions with stationary and moving objects, different forms of the same source of information can serve different functions. Differential parallactic displacements are this source. When one is considering stationary objects, following Equation 1, they can be used to detect a collision or bypass and to detect the direction of one's aimpoint. However, when one is considering a moving object, following Equations 4–6, they can only be used to detect collision or bypass; aimpoint seems unavailable.

This corollary aside, however, directed perception insists that a *satisficing* research strategy (Simon, 1950) is potentially dangerous. Once one has found one source of experimentally adequate information, one's job is not necessarily complete. For situations of collision and noncollision, then, this means that differential parallactic displacements may not be the sole source of information used. Thus, although in Experiment 4 we demonstrated that these displacements were sufficient for observers to perform the task, the rotational motion of the moving object with which the observer may collide may also be used, even though it is not nearly as potent a source. In addition, the feedback from eye movements may also be used, although we sug-

Table 2
Decision Tree for the Detection of Collisions and Bypasses With Stationary and Moving Objects When Traversing Linear Paths

Decision	Choice
Step 1	
Is the fixated object rigidly attached to the environment?	If yes, go to Step 2. If no, go to Step 3.
Step 2	
Are there any differential parallax displacements around the fixated object?	If no, a collision with the fixated object may be imminent. If a collision is desired, start monitoring τ_L. If a collision is not desired, take evasive action. If yes, a collision with the fixated object is not generally imminent. If a collision is desired, adjust one's velocity or path to null parallax, and start monitoring τ_L. If a collision is not desired, maintain course.
Step 3	
What is the nature of the differential parallax displacements around the fixated object?	If objects or textures in the foreground move faster than those in the background, a collision may be imminent. If a collision is desired, start monitoring τ_L. If a collision is not desired, take evasive action. If objects or textures in the background move in a retrograde manner, a collision will not generally occur and one will pass in front of the moving object. If a collision is desired, adjust velocity or one's path, canceling the retrograde motion until a lamellar field is attained, and then start monitoring τ_L. If a collision is not desired, maintain course. If objects or textures in the foreground and background move at about the same velocity, a collision will not generally occur and one will pass behind the moving object. If a collision is desired, adjust velocity or one's path until the lamellar field is attained, and then starting monitoring τ_L. If a collision is not desired, maintain course.

gest that this information is also not nearly as potent. In our situation, and in many others, the organism stands to benefit by using as many sources of information as it can. In summary, then, all we can contend is that differential parallactic displacements are adequate to the task and are likely to be used in most natural situations.

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ISSUES: ____ MISSING ____ DAMAGED

TITLE	VOLUME OR YEAR	NUMBER OR MONTH

Thank you. Once a claim is received and resolved, delivery of replacement issues routinely takes 4–6 weeks.

———— (TO BE FILLED OUT BY APA STAFF) ————

DATE RECEIVED: _____   DATE OF ACTION: _____
ACTION TAKEN: _____   INV. NO. & DATE: _____
STAFF NAME: _____   LABEL NO. & DATE:_____

Send this form to APA Subscription Claims, 750 First Street, NE, Washington, DC 20002-4242

PLEASE DO NOT REMOVE. A PHOTOCOPY MAY BE USED.