
Visual guidance of intercepting a moving target on foot

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Abstract. How do people walk to a moving target, and what visual information do they use to do so? Under a pursuit strategy, one would head toward the target's current position, whereas under an interception strategy, one would lead the target, ideally by maintaining a constant target-heading angle (or constant bearing angle). Either strategy may be guided by the egocentric direction of the target, local optic flow from the target, or global optic flow from the background. In four experiments, participants walked through a virtual environment to reach a target moving at a constant velocity. Regardless of the initial conditions, they walked ahead of the target for most of a trial at a fairly constant speed, consistent with an interception strategy (experiment 1). This behavior can be explained by trying to maintain a constant target-heading angle while trying to walk a straight path, with transient steering dynamics. In contrast to previous results for stationary targets, manipulation of the local optic flow from the target (experiment 2) and the global optic flow of the background (experiments 3 and 4) failed to influence interception behavior. Relative motion between the target and the background did affect the path slightly, presumably owing to its effect on perceived target motion. We conclude that humans use an interception strategy based on the egocentric direction of a moving target.

1 Introduction

To be successful in everyday behavior, locomotion must be coordinated with a complex, dynamic environment. Consider the children's game of tag, in which a player must steer toward stationary goals, intercept moving targets, avoid stationary and moving obstacles, and evade pursuers. Similar challenges are faced by animals in the wild, humans walking in public spaces, and mobile robots in realistic environments. Here, we examine human interception of a moving target, as part of a larger research program of investigating the elementary locomotor behaviors (Fajen and Warren 2003; Warren and Fajen, in press). A prototypical example of interception is a predator chasing its fleeing prey, and such behavior has become an integral part of sports like American football, where defensemen chase and tackle the ball carrier in the open field. In the present study, we examine the behavioral strategy that people use to walk to a moving target, and the visual information used to guide this strategy. In a companion article, we describe a dynamical model of interception behavior based upon a previous model of steering and obstacle avoidance (Warren and Fajen, submitted).

We approached the moving-target problem by first identifying idealized behavioral strategies and informational variables that might be used to perform this task, and then testing them experimentally. We use the term *strategy* to refer to a particular behavior pattern that would lead to successful performance. Each strategy could be controlled by one or more types of *information*. Let us consider two simple strategies and four types of information that could guide locomotion to a moving target.

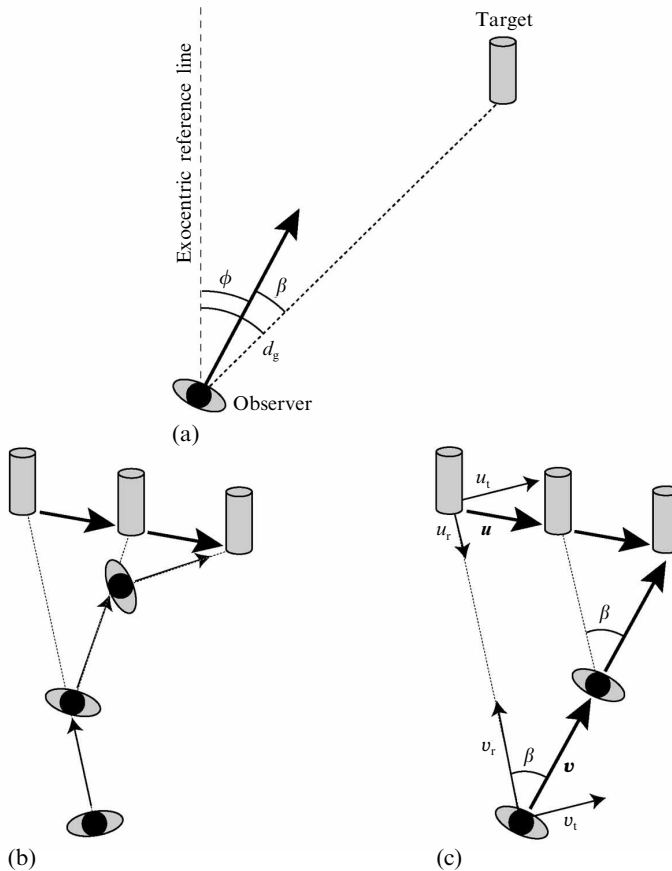


Figure 1. Strategies for walking to a moving target. (a) Basic variables; (b) pursuit strategy; (c) interception strategy.

1.1 Strategies

Suppose an agent locomotes with velocity v and a target moves with velocity u . Let us define the target-heading angle β as the visual angle between the agent's current direction of locomotion or heading and the direction of the goal or target, which is a distance d_g from the agent (figure 1a).

1.1.1 Pursuit. One possible strategy is to pursue the target by simply walking toward it at each moment, such that the target-heading angle is zero ($\beta = 0$) (see figure 1b). In addition, the agent's speed must be great enough for the distance to the goal d_g to decrease. This is the way in which humans typically walk to a stationary goal (Fajen and Warren 2003). With a moving target, however, the agent would have to turn continually to keep the heading direction aligned with the target, yielding a curved path of locomotion.

1.1.2 Interception. An alternative strategy is to intercept the target by walking ahead of it, such that the target-heading angle is greater than zero ($\beta > 0$). One version of this strategy familiar to sailors and pilots is to keep the target at a constant bearing angle, which corresponds to a collision course (if the agent is facing in the direction of travel). More generally, maintaining a constant positive target-heading angle and a straight path will lead to a successful interception,⁽¹⁾ on the assumption that the target is traveling at a constant velocity.

⁽¹⁾Merely holding the target-heading angle constant can also yield spiral paths about the target (cf Lee 1998), hence the added straight-path constraint.

As can be seen in figure 1c, this solution is equivalent to matching the target's transverse speed ($v_t = u_t$) and simultaneously walking toward it ($v_r > u_r$, where the subscript r indicates the radial speed along the line of sight) so that distance d_g decreases (see Appendix). This yields a straight path with a constant interception angle, given by

$$\hat{\beta} = \arcsin\left(\frac{u_t}{\|v\|}\right), \quad (1)$$

where $\|v\|$ is the agent's speed. Note that the agent has two control variables, the direction and speed of travel; adopting a different walking speed produces a different interception angle. It is important to point out that the agent need not explicitly match u_t or compute $\hat{\beta}$, for nulling the change in β and trying to walk a straight path will yield a successful interception at the constant angle $\hat{\beta}$. Even if the target velocity changes, such a continuous control strategy will be successful as long as $\|v\| > u_t$, although the resulting path may be curved.

Such a constant-interception-angle strategy was previously proposed for outfielders running to catch a fly ball, to control their transverse speed (Chapman 1968; Michaels and Oudejans 1992), and for pedestrians trying to avoid collisions (Cutting et al 1995). Some empirical evidence seems to favor this strategy. Lanchester and Mark (1975) found that teleost fish often track pieces of food using an interception strategy. Recently, Lenoir et al (1999a) reported that participants riding a tricycle along a track to intercept a moving target adjust their speed to maintain a constant target-heading angle. A similar result has also been found for participants walking on a variable-speed treadmill to intercept a virtual ball (Chardenon et al 2002). However, in these cases the participant was restricted to a straight path and could only vary speed, so it is not clear whether the same strategy would be used in the open field when both direction and speed can be controlled.

In an open-field setting, Rushton et al (1998) reported that participants actually did not anticipate the future position of a moving target but walked in its current visual direction, consistent with a pursuit strategy. However, target speed was slow (roughly 1 deg s^{-1} at the beginning of a trial) and participants were wearing displacing prisms at the time, so this may not reflect behavior with faster targets.

1.2 Information

To visually guide either one of these strategies, an observer could use any of the following types of information (refer to figure 2).

1.2.1 Egocentric direction. Let us define the locomotor axis as a walking observer's direction of travel, specified proprioceptively (Telford et al 1995); this is distinct from the body's antero-posterior (A-P) axis, because one can adopt a 'crabbing' gait. The egocentric direction of a target can then be defined as the visual direction of the target with respect to the locomotor axis,⁽²⁾ which corresponds to the target-heading angle. In a pursuit strategy based on egocentric direction the observer could simply align the felt locomotor axis with the target, bringing β to zero (see figure 2a). An interception strategy based on egocentric direction could maintain a constant positive angle between the felt locomotor axis and the target (see figure 2d). If the observer is facing in the direction of travel (so the A-P axis is aligned with the locomotor axis), this is equivalent to maintaining the target at a constant bearing angle, or at a constant angle of gaze. Both strategies also require that the perceived distance of the target must decrease, perhaps based on local optical expansion or binocular distance information.

⁽²⁾If the observer is facing in the direction of travel, then the locomotor axis and A-P axis are aligned and the egocentric direction of the target is equivalent to its bearing.

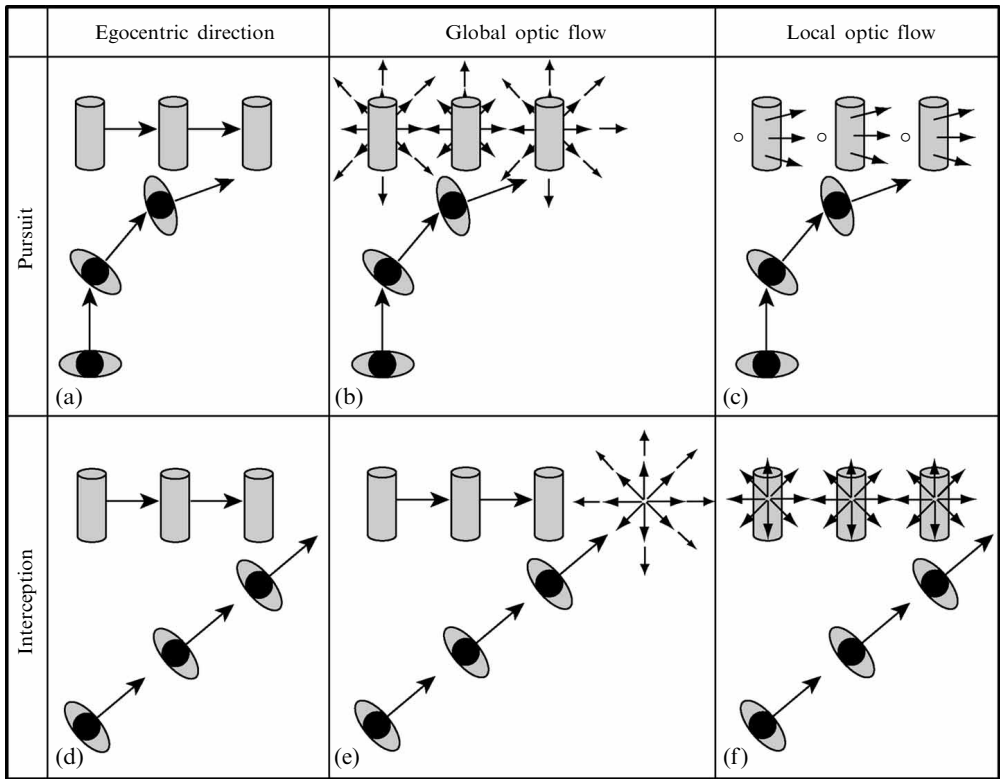


Figure 2. Illustration of the two strategies (pursuit and interception) and three sources of information (egocentric direction, global optic flow, and local optic flow) for walking to a moving target.

1.2.2 Global optic flow. Gibson (1950, 1958/1998) observed that the direction of locomotion is also specified by optic flow, the pattern of motion in the optic array projected to a moving observation point. He proposed that optic flow could be used to steer to a goal by aligning the focus of expansion, which specifies the heading point, with the target, or by magnifying the target itself in the field of view. Given that optic flow is detected by the eyes, and the eyes often rotate to maintain fixation, heading must be determined from the motion pattern on the retina, or retinal flow. Previous studies have demonstrated that observers can accurately determine their direction of heading whether or not their eyes are rotating, on the basis of both optical and extra-retinal information (Royden et al 1994; Li and Warren 2000; see Warren 2003, for a review). Thus, here we describe and experimentally manipulate the optic flow available to an observer under free-fixation conditions.

The observer's direction of heading is specified by the global optic flow from the stationary background, and thus it provides information for the target-heading angle. In a pursuit strategy based on global optic flow, an observer could visually align the perceived heading with the target (see figure 2b). For an interception strategy, the observer could maintain a constant visual angle between the perceived heading and the target (see figure 2e). In addition, optical expansion of the target would ensure that the distance to the target is decreasing.

1.2.3 Local optic flow. Local optic flow is also generated by the relative motion between the observer and the target itself, whether the observer, the target, or both are moving. Consequently, the motion pattern defined by the target's texture specifies the observer's

heading relative to a stationary or moving target.⁽³⁾ Thus, one way of implementing an interception strategy is to keep the heading specified by local flow within the contours of the moving target, yielding a straight interception path (figure 2f). This assumes that there is no additional component of flow due to rotation of the target. With a pursuit strategy, on the other hand, the heading specified by local optic flow will trail behind the moving target (figure 2c). In addition, local expansion of the target ensures that its distance is decreasing.

1.2.4 Binocular information. Binocular information is also available and might potentially be used to intercept a moving target. For example, the distance to the target, and hence over time its 3-D velocity, might be determined from binocular convergence, although it is only effective out to a couple of meters. Alternatively, motion disparity (the relative angular velocities of the target at the left and right eyes) specifies the passing distance in the frontal plane; that is, what the distance between the target and the observer will be at the moment of passage, in units of interocular distance (Regan 1993). Maintaining the passing distance at a value of zero would lead the observer to intercept the target on a straight path. Finally, the change in convergence or binocular disparity over time indicates whether the distance to the target is increasing or decreasing. Binocular information was not independently manipulated in the present experiments, but was consistent with egocentric direction and dissociated from optic flow.

Finally, particular variables of the retinal-flow field have been proposed for the case when the observer is fixating the moving target. For example, Cutting et al (1995) demonstrated that there are qualitative differences in the retinal flow of ground texture in front of and behind a moving target when the observer is on course to pass in front of, pass behind, or collide with it. However, such theories presume that the observer fixates the target (Cutting et al 1995; Kim and Turvey 1999; Wann and Swapp 2000), whereas numerous studies have demonstrated that observers can determine the direction of heading during pursuit eye movements when the observer is fixating elsewhere (Warren 2003). In the present experiments, we have chosen to begin with the more general case and manipulate the optic flow presented to an observer under free fixation conditions. If we find an influence of optic flow, this would suggest further research to test particular retinal-flow variables.

The information for walking to a stationary goal has received more study than that for a moving target. The optic-flow hypothesis was challenged by Rushton et al (1998; see also Harris and Bonas 2002), who asked participants to walk to a stationary goal while wearing displacing prisms. The prisms displaced both the image of the target and the optic-flow pattern. Thus, if participants steer to a goal by centering the optic flow on the target, they should still walk a straight path to the target, as they do normally. But their subjects took curved paths to the target, consistent with the use of egocentric direction.

On the other hand, Warren et al (2001) asked participants to walk to a stationary goal in a virtual environment. Optic flow was dissociated from egocentric direction by displacing the flow pattern from the actual direction of locomotion by 10°. Participants relied on both egocentric direction and global optic flow, but the latter increasingly dominated as more flow and motion parallax were added to the display, consistent with a linear combination model (see also Rogers and Allison 1999; Wood et al 2000; Harris and Carré 2001). Similar influences were observed by Wilkie and Wann (2002, 2003) for the task of steering curved paths to a stationary target in a driving simulator.

⁽³⁾If the target is moving in any direction other than parallel to the observer's path, the local optic flow pattern will specify a different heading than the global optic flow pattern (Warren and Saunders 1995).

They found linear weighted contributions of the visual direction of the target, retinal flow from the ground surface, and extra-retinal signals. The aim of the present study was to determine whether observers also rely on optic flow (and hence retinal flow) or egocentric direction in the case of walking to a moving target.

Cutting et al (1995) investigated the information observers use to judge whether they will collide with, pass in front of, or pass behind a moving object. Judgments were correlated with the rate of change in the simulated target-heading angle ($\dot{\beta}$), consistent with an interception strategy. The experiments demonstrated that interception judgments can be based on global retinal flow, specifically differential motion between the foreground and background about the target, and to a much weaker extent on local optic flow, specifically the change in orientation of the target. However, because the subjects were stationary, proprioceptive information about the locomotor axis was not available, and thus the contribution of egocentric direction was not tested. In addition, the displays simulated a pursuit eye movement to fixate the moving target. Here we tested active walking and the simpler case without simulated eye rotation.

Lenoir et al (1999b) tested the influence of background texture on the speed participants adopted when riding on a straight track to intercept a ball. When background texture was present, observers initially traveled faster than predicted by a constant target-angle strategy, but slowed down toward the end of the approach and intercepted the ball with a higher accuracy than when background texture was absent. They concluded that the initial speed adjustments resulted from a background-induced overestimation of target speed.

Thus, the roles of global optic flow, local optic flow, and egocentric direction in intercepting a moving target remain an open question. The purpose of the present study was to identify both the strategy and the information that humans use to walk to a moving target in a virtual environment. To determine which strategy was used (pursuit or interception), we analyzed the paths that they followed to targets with different trajectories. In addition, to identify the information upon which participants rely (egocentric direction, global optic flow, or local optic flow), we manipulated the visual properties of the background and the target.

2 General method

2.1 Apparatus

All four experiments were conducted in the Virtual Environment Navigation Lab (VENLab) at Brown University. Participants walked freely in a 12 m \times 12 m area while immersed in a virtual environment. The environment was generated on a graphics workstation (SGI Onyx2 IR) at 60 frames per second, and presented in a stereoscopic head-mounted display (HMD, Kaiser Electro-Optics Proview 80) with a 60° (horizontal) \times 40° (vertical) field of view, which was covered by a black isolation shield. Images were presented on two LCD displays (640 \times 480 pixels) and projected via lenses to the left and right eyes with binocular disparities that were computed for the corresponding views of a 3-D scene. The participant's head position and orientation were measured with a hybrid ultrasonic–inertial tracking system (Intersense IS-900) with six degrees of freedom, at a sampling rate of 60 Hz. Information from the tracking system was used to update the display with a latency of approximately three frames (\sim 50 ms).

2.2 Procedure

Prior to the experiment, the lens separation in the HMD was adjusted for the participant's interocular distance. To ensure that the stereo image pair could be fused, a random-dot stereogram of a rectangle was tested. Before each trial, two red markers appeared in the simulated environment. Participants prepared for a trial by standing on one marker and facing the other, to ensure that they were positioned and oriented correctly.

The color of the markers then changed from red to green, indicating that the participant should begin walking toward the distant marker. After 0.5 m, the markers disappeared and participants continued to walk and look in the same direction. After another 0.5 m, the moving target appeared in a controlled location. Target speed was 0.6 m s^{-1} in all experiments, about half the normal walking speed. Participants were instructed to walk to the moving target in a natural manner, and were free to look wherever they wanted. When they reached the target, it disappeared with a ‘popping’ sound. The red inter-trial markers reappeared and the participant prepared for the next trial by walking to the marker in front of them and turning around to face the other marker.

2.3 Data analysis

The computer recorded head orientation and the x and z coordinates of left eye position (at 30 Hz), which were used to calculate the x and z coordinates of the cyclopean point between the left and right eyes. Both time series (x and z) were filtered with a forward and backward 2nd-order low-pass Butterworth filter with a cutoff frequency of 0.6 Hz, to reduce the effects of gait oscillations. The filter compresses data points near the end of the time series, which introduces an artifactual drop in speed and target-heading angle. To eliminate these effects, the last 500 ms of the filtered time series were truncated. The filtered position data were used to compute the participant’s direction of motion (heading, ϕ) in exocentric coordinates (see figure 1a) in each frame according to the following equation:

$$\phi_i = \arctan\left(\frac{x_i - x_{i-1}}{z_i - z_{i-1}}\right), \quad (2)$$

where x_i and z_i are the head coordinates on the i th frame. The direction of the target (ψ) with respect to an exocentric reference axis was computed from the following equation:

$$\psi_i = \arctan\left(\frac{X_i - x_i}{Z_i - z_i}\right), \quad (3)$$

where X_i and Z_i are the coordinates of the target on the i th frame. The target-heading angle was computed as $\beta = \phi - \psi$. To compute the mean time series of target-heading angle for each condition, the time series for each trial was normalized to a length of 25 data points. For example, for a trial with 80 data points, the third data point was placed in the first bin, the sixth data point in the second bin, the ninth data point in the third bin, the twelfth data point in the fourth bin, the sixteenth data point was placed in the fifth bin, etc. The mean target-heading angle in each bin was then computed to yield a mean normalized target-heading-angle time series for each condition.

Walking speed in meters per second was computed by multiplying the displacement (in meters) on successive frames by 30, the number of frames recorded per second. Walking-speed time series were then normalized and averaged by the same procedure as described above.

To estimate path variability, we first calculated the mean position at each of the 25 time steps in all conditions. For each trial, we then calculated the Euclidean distance from the mean position in the corresponding condition. The average distance from the mean position at each time step was used to estimate path variability.

3 Experiment 1: Behavioral strategy and information

In experiment 1, we began our investigation of the contributions of local and global optic flow by manipulating the appearance of the target and the background, and examined the behavioral strategy by analyzing the participant’s path and the time

series of target-heading angle β . To vary the presence of local optic flow, the moving target was either a textured post that optically expanded, or a thin, untextured line with very little optical expansion. If local optic flow is necessary information for the guidance of walking, then walking behavior should be affected by eliminating it. To vary the presence of global optic flow, the target appeared either in a room with textured walls, floor, and ceiling, or in empty black space. If global optic flow provides necessary information, then behavior should be affected by removing the background. Note that the egocentric direction and binocular information about the target are available in all four conditions. Thus, if participants rely on this information, or upon combinations of redundant variables (Landy et al 1995), behavior would be similar across conditions.

3.1 Method

3.1.1 Participants. Eight undergraduate and graduate students participated in experiment 1. No participants reported having any visual or motor impairment. They were paid \$16 for their participation in the study.

3.1.2 Displays. After participants walked 1 m straight ahead, the target appeared at a distance of 3 m along the z axis either directly in front of the participant (Center condition) or 25° to the left of the participant's initial heading (Side condition; see figure 3), and moved rightward. These initial conditions were also mirrored left/right, and the data were collapsed. The trajectory of the target either crossed perpendicular to the participant's initial heading (0° , Cross condition), approached the participant at an angle of 30° to the perpendicular (Approach condition), or retreated at an angle of 30° (Retreat condition).

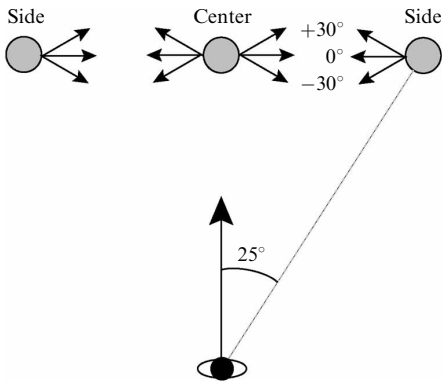


Figure 3. Top view of initial conditions used in experiment 1. The moving target appeared either directly in front of the observer (center) or 25° to the right or left (side) and either approached, crossed, or retreated from the observer's initial path of locomotion.

Two background conditions were crossed with two target conditions. In the Room condition, a room with textured walls, floor, and ceiling appeared at the same time as the target [7.5 m (depth) \times 10.4 m (width) \times 2.5 m (height)]. The participant was 1.5 m from the rear wall when the target appeared at a distance of 3 m along the z axis. In the No Room condition, the target moved through empty black space. The target was depicted as either a textured cylinder 2.5 m tall with a radius of 0.1 m (Post condition), or a thin, untextured line 0.0025 m wide (Line condition). In the Room condition, the base and top of the target were clearly visible where they met the floor and ceiling, providing information about target position and motion. In the No Room condition, the target line ran off the top and bottom of the display so that neither its base nor its top was visible.

Participants were instructed to walk to the target and pass through it, at which point the target disappeared. Contact with the target, which was indicated to participants by a 'popping' noise, was assumed to have taken place when the distance

between the participant's head position and the center of the target was less than or equal to 0.2 m, regardless of whether the target appeared as a post or a line. In the Room condition, if the target reached one of the side walls before the participant made contact with the target, then the target disappeared and the trial ended. In the No Room condition, an invisible rectangular boundary in the same location was used to determine when the target disappeared.

3.1.3 Design. The design for experiment 1 was 2 (target type) \times 2 (background) \times 2 (center/side location) \times 2 (left/right motion) \times 3 (target trajectory) with all variables within-participants. Trials were blocked by target type and background and block order was counterbalanced. There were two sessions, which were completed on consecutive days and consisted of two blocks each. Trials within each block were presented in a random order, and there were 5 repetitions per condition, yielding 60 trials per block and a total of 240 trials.

3.2 Results and discussion

3.2.1 Paths. The mean paths of locomotion in each condition are plotted in figure 4. The two columns correspond to the starting location of the target (Center, Side) and the rows to target trajectory (Approach, Cross, Retreat). In the Center conditions, participants gradually turn in the direction of the target motion and (in the Cross and Retreat conditions) eventually straighten out their path to reach the target. In the Side condition, participants turn smoothly toward the target, and either follow a straight path to the target (Approach condition) or subsequently reverse back again to track the target motion (Cross and Retreat conditions). There appear to be differences between the background and target conditions in some cases, but the data for target-heading angle permit a more sensitive analysis.

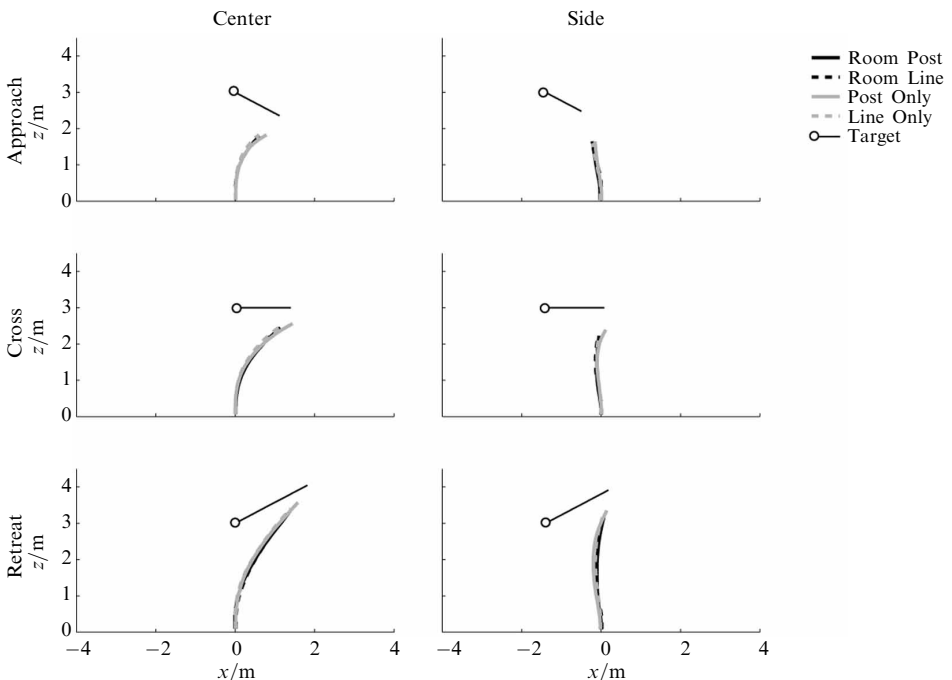


Figure 4. Mean paths of walking for the initial target locations and trajectories in experiment 1. Black and gray lines correspond to the Room and No Room conditions, respectively. Solid and dotted lines correspond to the Post and Line conditions, respectively.

3.2.2 Target-heading angle. The mean time series of target-heading angle for each condition is plotted in figure 5. In the Center condition, the target appeared directly in front of the participant, so the initial angle was zero ($\beta = 0^\circ$), then it dipped slightly, gradually increased to between 10° and 20° . The small initial dip is due to the fact that the moving target briefly led the heading while participants were still walking straight ahead. In the Side condition, the initial target-heading angle was 25° and then decreased to a plateau between 10° and 20° . Thus, contrary to the predictions of a pursuit strategy, participants walked ahead of the moving target for most of the trial regardless of initial conditions. Note, however, that the target-heading angle did not achieve a constant value as predicted by an idealized interception strategy, but usually remained below the predicted values of 23.8° , 27.7° , and 23.8° in the Center condition (Approach, Cross, and Retreat, respectively) and 24.9° and 26.7° in the Side condition (Cross, Retreat), although it did plateau near the predicted 15.5° in the Side/Approach condition (calculated for the mean maximum v of 1.29 m s^{-1}).

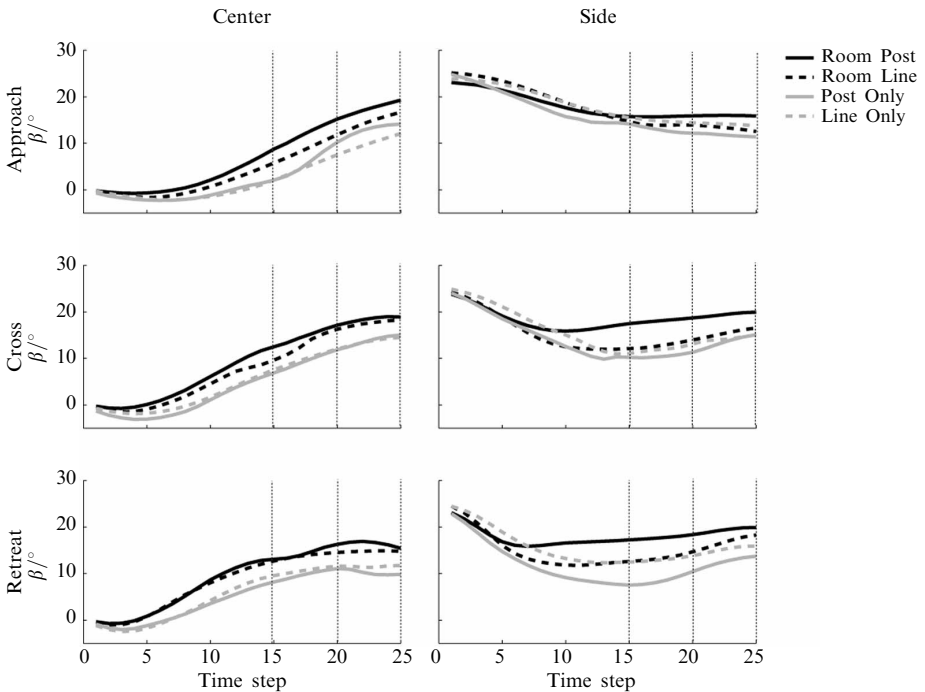


Figure 5. Mean time series of target-heading angle (β) for the initial target locations and trajectories in experiment 1. Black and gray lines correspond to the Room and No Room conditions, respectively. Solid and dotted lines correspond to the Post and Line conditions, respectively. Individual trials were normalized to a length of 25 time steps to allow for comparison between conditions (see section 2). Mean and standard deviation of trial duration in each condition was as follows: 2.38 s (SD = 0.30 s) in Center/Approach, 1.95 s (SD = 0.11 s) in Side/Approach, 2.95 s (SD = 0.29 s) in Center/Cross, 2.65 s (SD = 0.44 s) in Side/Cross, 3.69 s (SD = 0.40 s) in Center/Retreat, and 3.27 s (SD = 0.28 s) in Side/Retreat.

To evaluate the effects of target type and background, we performed ANOVAs on the mean value of β in the 15th, 20th, and 25th bin (60%, 80%, and 100% of the trial, respectively). Because we were mostly interested in the effects of background and target type, we ran six separate 2 (background) \times 2 (target) \times 3 (time step) ANOVAs, one for each condition of starting location and target trajectory. The results of all six ANOVAs are summarized in table 1. The main effect of time step was significant in all six conditions, confirming that the target-heading angle changed over the course

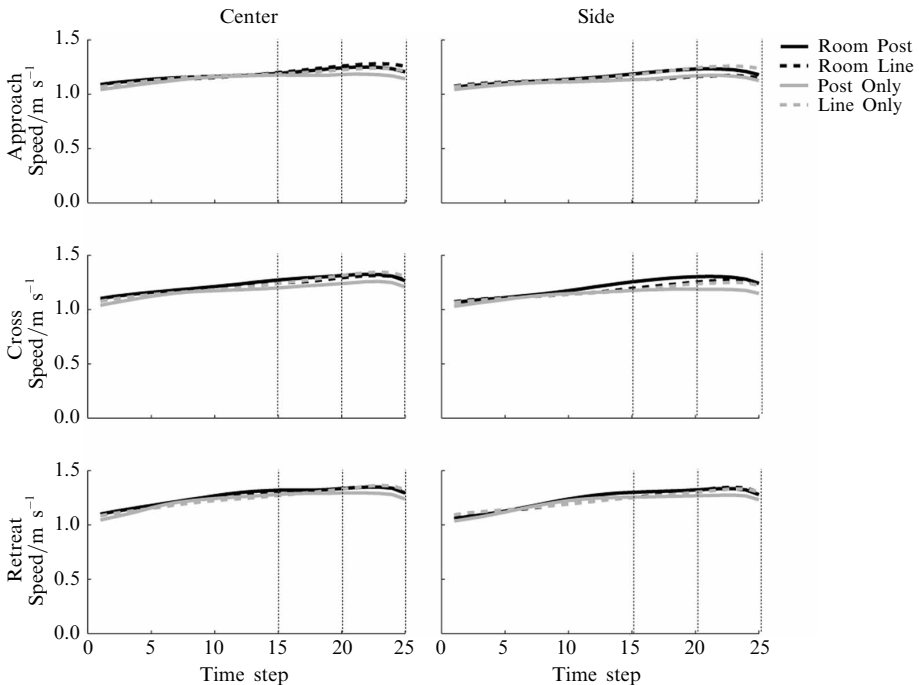
Table 1. *F*-values for ANOVAs in experiment 1.

	Center			Side		
	Approach	Cross	Retreat	Approach	Cross	Retreat
Target angle, β						
Background	25.20**	7.79*	8.159*	0.67	4.95	15.95**
Target	1.73	0.12	0.01	0.02	1.08	0.01
Time	54.59***	105.28***	9.05**	5.46*	21.72***	38.51***
Walking speed						
Background	0.69	0.36	0.55	0.04	2.01	0.55
Target	4.70	5.77*	1.59	0.16	0.01	1.30
Time	2.29	4.15	3.02	4.83	3.45	2.22

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

of the trial. In addition, there was a significant main effect of background in all conditions except the Side/Approach and Side/Cross conditions, for the mean target-heading angle was greater with the Room than No Room (see figure 5). In contrast, the main effect of target type was not significant in any of the conditions. None of the interactions were significant. Thus, the statistical analyses of target-heading angle reflect the pattern evident in the time series of figure 5. The results indicate a small influence of the background, but no influence of local flow from the target. Moreover, these effects were generally consistent across different initial conditions.

3.2.3 Walking speed. Mean time series of walking speed for each condition are plotted in figure 6. The overall mean initial walking speed at the moment the target appeared was 1.07 m s^{-1} . It increased gradually over the course of the trial to a mean maximum walking speed of 1.29 m s^{-1} , and then dropped slightly to mean final walking speed of 1.24 m s^{-1} near the end of the trial. This pattern was quite consistent across all conditions.

**Figure 6.** Mean time series of walking speed in experiment 1. See figure 4 caption for explanation of different conditions.

We performed statistical analyses to test the effects of background and target on walking speed at the 15th, 20th, and 25th time step. Six separate ANOVAs for each condition of starting location and target trajectory were run, the results of which are summarized in table 1. With one exception, none of the effects of background, target type, or time step were significant. The one exception was the effect of target type in the Center/Cross condition, $F_{1,7} = 5.77$, $p < 0.05$, which indicated that participants walked slightly faster in the Line condition ($M = 1.28 \text{ m s}^{-1}$) than they did in the Post condition ($M = 1.25 \text{ m s}^{-1}$). This confirms the observations based on figure 6 that walking speed was generally unaffected by background or target type.

3.2.4 Path variability. If people rely on more than one source of information, then removing a source of information may affect the variability in the interception path. Mean path variability for each condition is plotted in figure 7. Overall, variability gradually increases throughout the first part of the trial before leveling off, probably because the position of the target constrains the position of the observer as he or she intercepts it. There was a trend towards more variability in the No Room condition for some initial conditions, but none of the main effects or interactions was statistically significant, with one exception: there was a time step effect in the Center/Retreat condition ($F_{2,14} = 5.24$, $p < 0.05$).

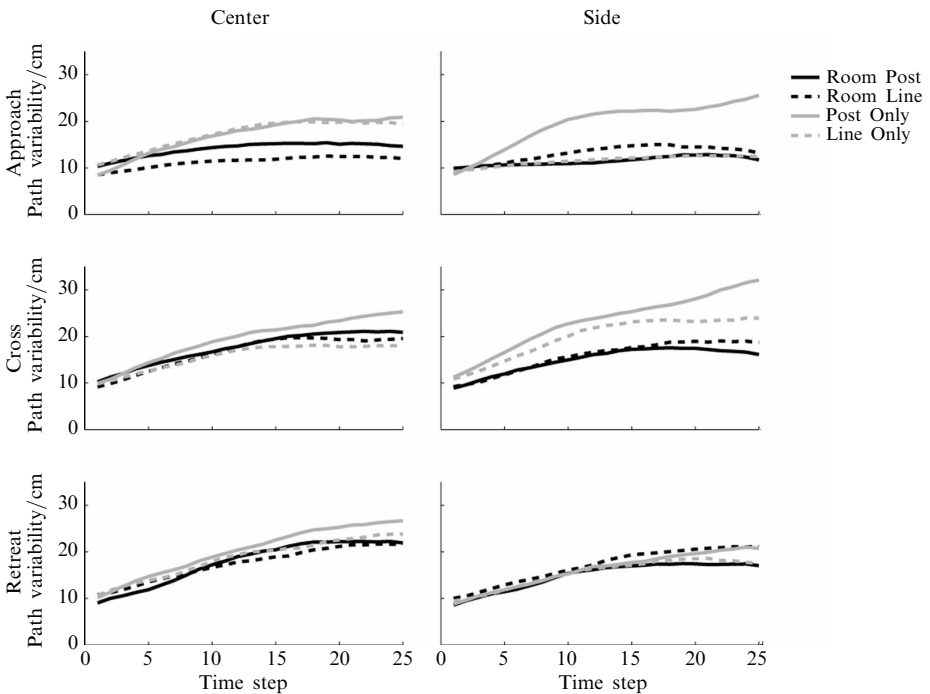


Figure 7. Mean path variability in experiment 1. See figure 4 caption for explanation of different conditions.

In sum, there are three major findings of experiment 1. First, target-heading angle appeared to converge from different initial conditions to a value between 10° and 20° , indicating that participants walked ahead of the target at a roughly constant speed for most of the trial. This result contradicts a pursuit strategy, which predicts that participants should walk directly toward the target ($\beta = 0^\circ$). However, the pattern of behavior did not match the simple prediction of a constant interception angle either, for participants did not actually hold β constant and seldom reached the predicted $\hat{\beta}$ value.

This could be due to the fact that initial target distance (3 m) and mean trial duration (3 s) were rather short, so they did not have time to achieve a constant β .

The second main finding is that behavior remained the same whether the target was an expanding post or a narrow line. The simplest interpretation of this result is that participants do not rely on local optic flow. However, it is possible that participants used local optic flow in the Post condition, and redundant global optic flow or egocentric direction information in the Line condition. We consider this possibility in experiment 2 by independently manipulating the local optic flow.

Third, behavior was affected by the presence of a background. The target-heading angle grew more rapidly to somewhat higher values in the Room condition than the No Room condition. Nevertheless, the basic forms of the paths and time series were the same, indicating that information from the target alone is sufficient for interception. One possibility is that, because global optic flow was redundant with egocentric direction, their combined influence yielded a faster turning rate and greater angle in the Room condition. Another possibility is that the presence of a stationary background enhanced the perception of target motion. We explored this issue in more detail in experiments 3 and 4 by manipulating global optic flow independently of egocentric direction.

4 Experiment 2: Local optic flow

The purpose of experiment 2 was to test the contribution of local optic flow to interception behavior. In most natural conditions, and those of experiment 1, egocentric direction, global optic flow, and local optic flow provide redundant information about the target-heading angle. To dissociate them, we manipulated local optic flow by rotating the target about a vertical axis, and eliminated the background. Relying on local optic flow would thus yield a different approach path than relying on egocentric direction.

This can be illustrated as follows. In figure 8a, the agent is executing an interception strategy that maintains a constant target-heading angle β . The only relative motion between the agent and the target is along the radial axis, yielding a heading from local flow aligned with the target. The absence of relative motion along the transverse axis means that the same side of the target continues to face the agent. Now suppose that the observer in figure 8b follows a path that is 10° to the left of the interception path, such that the target-heading angle decreases. This shifts the heading from local flow by 10° to the left of the target, and the left side of the target begins to come into view during the approach.

By rotating the target about a vertical axis, we can reproduce the local optic flow pattern in figure 8b for an agent that is actually on an interception course. The observer in figure 8c is on an interception path with a constant target-heading angle, but the target is rotating counterclockwise about a vertical axis, adding a rightward component of local optic flow. This shifts the heading from local optic flow to the left by 10° , analogous to figure 8b, and more of the left side of the target comes into view. If the agent is using the local optic flow to intercept the target, this would lead to walking rightward to shift the heading from local optic flow back on the target, yielding a larger interception angle (figure 8d); the agent also keeps facing the same side of the target. If, on the other hand, the agent relies on the egocentric direction of the target, she/he should be unaffected by this manipulation of local optic flow.

4.1 Method

4.1.1 *Participants.* Nine undergraduate and graduate students participated in experiment 2. No participants reported having any visual or motor impairment. Participants were paid \$8 for their participation in the study.

4.1.2 *Displays.* The displays were similar to those used in the Center/No Room/Post condition of experiment 1, with a few changes. The target appeared directly in front of

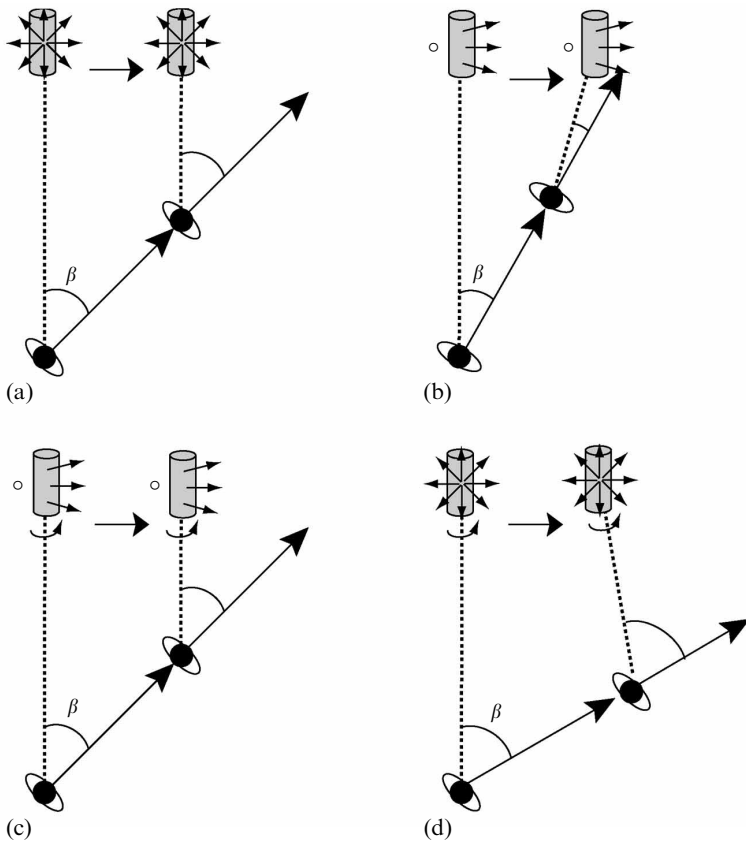


Figure 8. Illustration of the manipulation of local optic flow used in experiment 2. (a) Interception path: agent and target have the same transverse velocity, so their relative motion consists solely of an approach. The local heading point is thus centered on the target. (b) The agent's path is 10° to the left of the interception path, so the local heading point appears 10° to the left of the target. (c) Interception path with rightward (counterclockwise) rotation of the target, which shifts the local heading point 10° to the left of the target. (d) To keep the local heading point on the target, the agent compensates by turning 10° to the right.

the observer and moved through empty black space. First, initial target distance along the z axis was 4 m rather than 3 m, which increased the trial duration and allowed us to collect longer samples. Second, only the Cross (0°) and Retreat (30°) target trajectories were presented. Third, the trial ended and the target disappeared if the target reached an invisible border 6 m to the right or left of its initial position before the participant made contact with the target. Fourth, the target was a cylindrical post covered by a fine, wood-grained texture and 8 brightly colored, vertical stripes, providing detail at both near and far distances. Thus, local optic flow was made more salient and global optic flow was eliminated, enhancing the conditions for use of local optic flow.

The local optic flow was manipulated to correspond to a heading direction that was offset from the actual walking direction by 0° , $\pm 10^\circ$, $\pm 20^\circ$, or $\pm 40^\circ$. To explain the details of the manipulation, let point A be a point on the surface of the target facing the observer and point B be a point at the center of the target (on its longitudinal axis). For a nonrotating target, the relative optical velocity of these two points is zero if and only if the observer is on a constant-interception-angle path. The more the observer departs from a constant-interception-angle path, the greater the relative optical velocity of points A and B. On each frame, the computer calculated the relative optical velocity of points A and B for the observer's current path and for an observer

walking to the left or right by an amount equal to the offset angle. The difference between these relative optical velocities corresponds to the difference in local optic flow between the actual and offset heading directions, and determines the amount of target rotation. Thus, the relative optical velocity of points A and B would be zero if and only if the observer's path deviated from a constant-interception-angle path by an amount equal to the offset angle.

4.1.3 Design. The design for experiment 2 was 2 (target trajectory) \times 2 (left/right motion) \times 7 (offset angle). All variables were within-participants and trials were presented in a completely random order. There were 4 repetitions per condition for a total of 112 trials.

4.2 Results and discussion

4.2.1 Target-heading angle. The mean time series of target-heading angle for each condition appear in figure 9. Similar to the Center/No Room condition of experiment 1, β increased from 0° to between 10° and 15° . This is again consistent with an interception strategy. Most importantly, there was no influence of the flow offset on mean target-heading angle. In separate ANOVAs for the two target trajectory conditions (see table 2), there were no significant main effects or interactions involving offset angle, confirming that local optic flow did not influence target-heading angle.

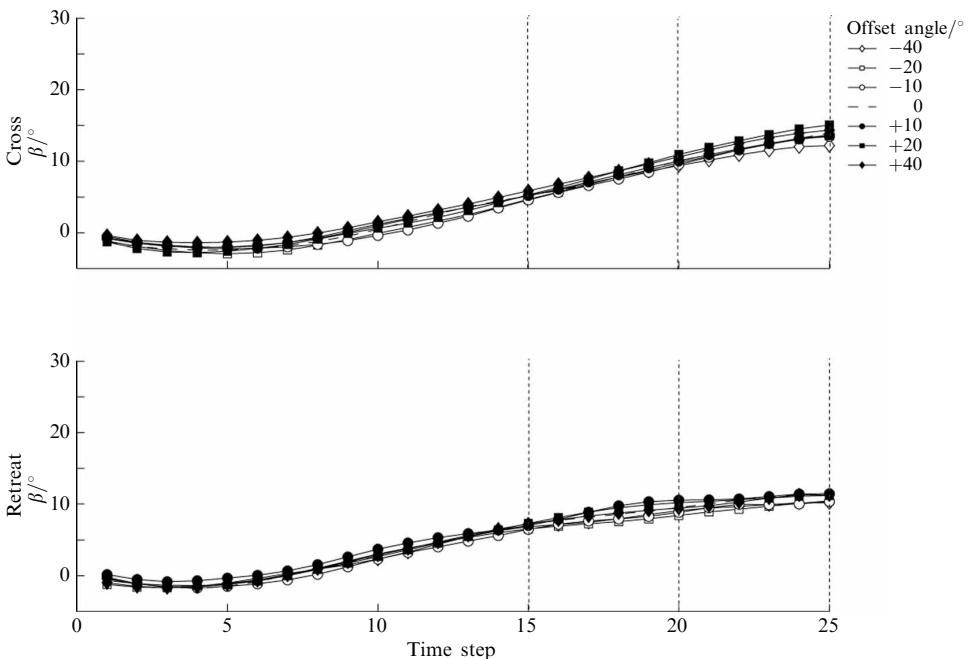


Figure 9. Mean time series of target-heading angle in experiment 2 for the Cross (top panel) and Retreat (bottom panel) conditions. Different lines correspond to different offset angle conditions.

4.2.2 Walking speed. Mean walking speed time series for both target trajectories appear in figure 10. The overall mean initial walking speed at the moment that the target first appeared was 1.20 m s^{-1} , and it gradually increased for most of the trial to a mean maximum walking speed of 1.42 m s^{-1} before decreasing slightly to a mean final walking speed of 1.30 m s^{-1} . These data are quite consistent with the results from experiment 1. Separate ANOVAs for the two target trajectory conditions confirmed that there were no effects of offset angle on walking speed (see table 2), consistent with the interpretation that participants do not rely upon local optic flow to intercept a moving target. This time, the effect of time step reached significance.

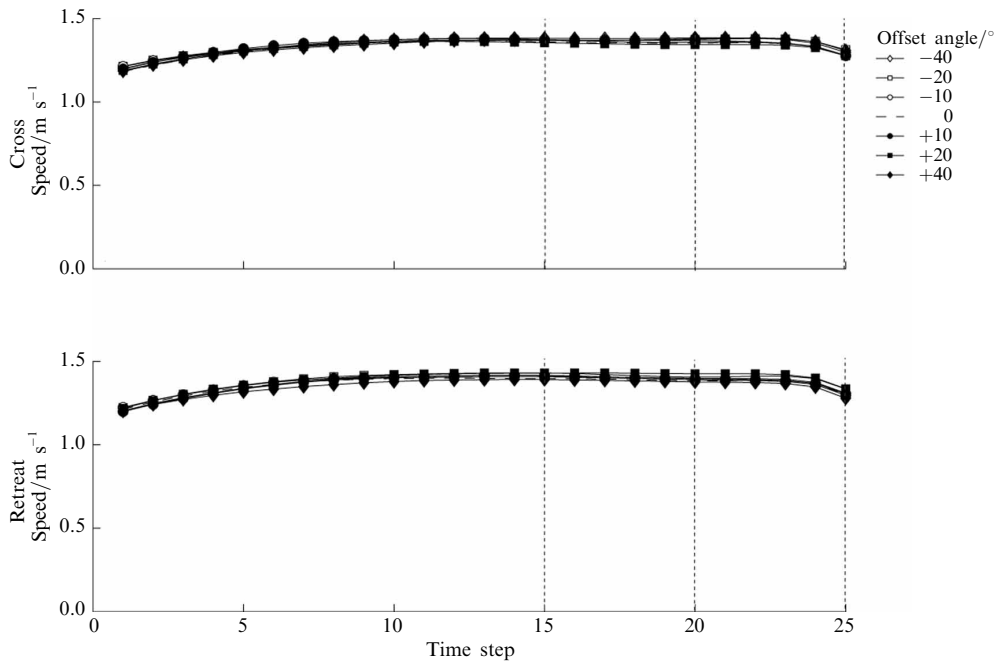


Figure 10. Mean time series of walking speed in the Cross (top panel) and Retreat (bottom panel) conditions of experiment 2. Different lines correspond to different offset angle conditions.

4.2.3 Path variability. As in experiment 1, path variability gradually increased throughout the first part of the trial before leveling off. The effect of offset angle was not statistically significant in either the Cross or Retreat conditions.

The purpose of experiment 2 was to test whether participants would be influenced by local optic flow when it was placed in conflict with egocentric direction. The results indicate that interception behavior is unaffected by the manipulation of local optic flow, but remains consistent with the use of egocentric direction. It is important to point out that the display contained no background optic flow and the target itself had quite salient texture, so the conditions were optimal for using local optic flow. The results thus strongly suggest that participants do not rely upon local optic flow to control steering when intercepting a moving target.

5 Experiment 3: Global optic flow

In experiment 3, we tested the contribution of global optic flow to interception behavior. In principle, the current target-heading angle β could be determined from the angle between the visual direction of the goal and the current heading specified by global optic flow, or from the egocentric direction of the goal with respect to the proprioceptive locomotor axis. To dissociate these two hypotheses, we manipulated the global optic flow by adding motion to the background.

We can illustrate the manipulation as follows. The observer in figure 11a is traveling on an interception path with a constant target-heading angle. The global optic flow from the background specifies the current heading direction, and thus the angle between the heading point and the target also remains constant over time ($\beta_1 = \beta_2$). In figure 11b, the observer is walking 10° to the left of the interception path, so the target-heading angle decreases over time ($\beta_1 > \beta_2$). By moving the background, we can reproduce the global optic flow pattern in figure 11b for an observer who is actually on a correct interception path. The observer in figure 11c is on a correct interception path (like the observer in figure 11a), but the background is moving to the right,

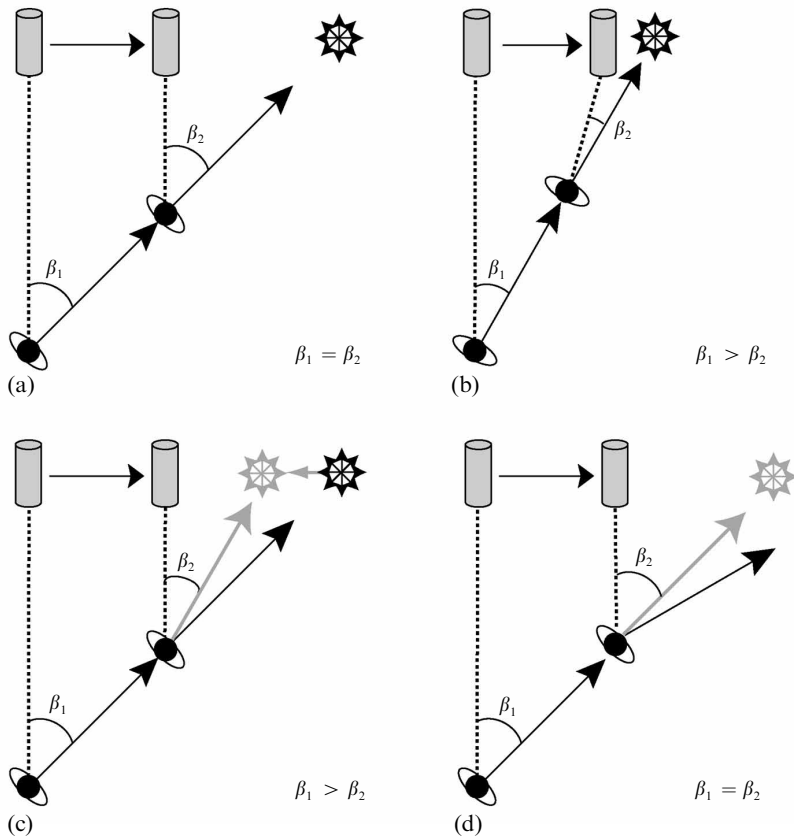


Figure 11. Illustration of the manipulation of global optic flow used in experiment 3. (a) Interception path with a constant angle between the global flow pattern and the target. (b) The agent's path is 10° to the left of the interception path, producing a decreasing target-heading angle. (c) Shifting the global flow pattern 10° to the left of the actual interception path (black arrow) yields a decreasing perceived target-heading angle, specifying an offset path 10° to the left (gray arrow). (d) To maintain a constant perceived target-heading angle, the agent compensates by turning 10° to the right, yielding an increasing angle between the target and the actual heading (black arrow).

which shifts the global optic flow pattern to the left. The result is that the perceived target-heading angle decreases as in figure 11b. To keep a constant perceived target-heading angle, the observer would compensate by walking to the right (as in figure 11d) or by walking faster, creating an increasing angle between the target and the actual heading. Alternatively, if egocentric direction rather than global optic flow is used, behavior should be unaffected by this manipulation.

5.1 Method

5.1.1 Participants. Eight undergraduate and graduate students participated in experiment 3. None reported having any visual or motor impairment. They were paid \$8 for their participation in the study.

5.1.2 Displays. Displays were similar to those in the Center/Room/Line condition of experiment 1, with a few exceptions. A wider room was used (10 m deep \times 25 m wide \times 2.5 m high) to keep the target from reaching the walls, which moved independently, before the participant could intercept the target. To eliminate any influence of local optic flow, the moving target was an untextured red line with a radius of 0.01 m. Initial target distance (4 m), starting location (Center), and target trajectories (Cross and Retreat) were the same as in experiment 2. After the markers changed color and the

room appeared, the participant waited 1 s for the markers to disappear before starting to walk straight ahead; the target then appeared after the participant had walked 1.0 m. If the target reached an invisible border 4 m to the left or right of its initial position before the participant intercepted it, the target disappeared and the trial ended.

To explain the details of the global optic flow manipulation, consider the change in the angle between the target and heading specified by global optic flow (ie the target-visual-heading angle). When optic flow is not manipulated, the change in target-visual-heading angle is zero if and only if the observer is walking on a constant interception angle path. Deviations from the constant interception angle path will result in changes in the target-visual-heading angle. On each frame, the computer calculated (i) the change in the target-visual-heading angle for the observer's current path, and (ii) the change in the target-visual-heading angle for an observer walking to the left or right by an amount equal to the offset angle. To make the target-visual-heading angle change as if the observer was walking in the offset direction, the flow pattern was shifted by an angle equal to the difference between (i) and (ii). This shift was achieved by rotating the room about the observer. Thus, the change in target-visual-heading angle would be zero if and only if the observer's path deviated from the constant-interception-angle path by an amount equal to the offset angle. Seven offset angles were used: 0° , $\pm 5^\circ$, $\pm 10^\circ$, and $\pm 20^\circ$. Positive offset angles corresponded to shifts in the global flow ahead of the target and negative offset angles corresponded to shifts behind the target.

5.1.3 Design. The design for experiment 3 was 2 (target trajectory) \times 2 (left/right motion) \times 7 (offset angle). All variables were within-participants. Trials were presented in a completely random order. There were 4 repetitions per condition for a total of 112 trials.

5.2 Results and discussion

5.2.1 Target-heading angle. Mean time series of target-heading angle appear in figure 12. As in the Room condition of experiment 1, β increased from 0° to between 15° and 25° . More importantly, target-heading angle was greater when the global flow pattern was

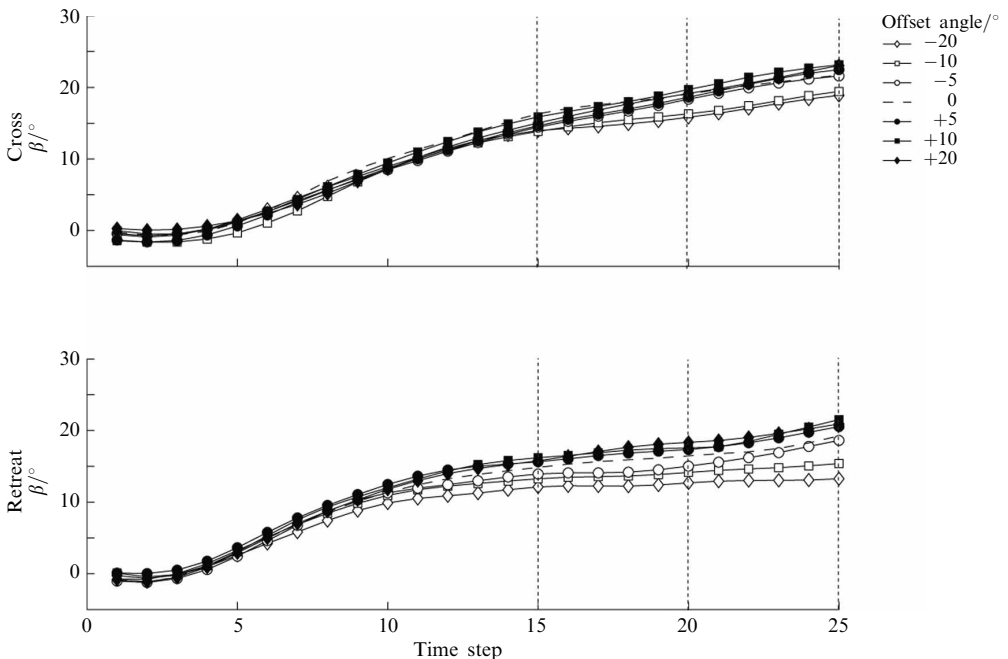


Figure 12. Mean time series of target-heading angle in the Cross (top panel) and Retreat (bottom panel) conditions of experiment 3. Curves correspond to different offset angle conditions.

offset in the same direction as the target motion (ie positive offset angles), and progressively smaller when the flow pattern was offset in the opposite direction (negative offset angles). Surprisingly, however, the direction of this effect was opposite to that which would be expected if participants used global optic flow. Separate ANOVAs for both target trajectory conditions revealed significant main effects of offset angle (see table 2). In addition, we ran six planned comparisons to test the differences between the 0° offset condition and all other offset conditions at the 25th time step. These analyses revealed significant ($p < 0.05$) differences at the -10° and -20° offsets for both trajectory conditions. The only positive offset condition that reached significance was $+5^\circ$ in the retreat trajectory, suggesting that the effect of the flow offset angle was asymmetric. We will discuss the direction of this offset below.

Table 2. *F*-values for ANOVAs in experiments 2 and 3.

	Target angle, β		Walking speed	
	Cross	Retreat	Cross	Retreat
Experiment 2				
Offset	0.95	1.20	0.99	1.83
Time	510.24***	58.90***	18.90***	42.29***
Offset \times Time	1.62	0.66	1.53	0.64
Experiment 3				
Offset	4.54*	8.15**	2.22	0.74
Time	88.04***	31.84***	31.33***	28.27***
Offset \times Time	2.52	3.08	0.69	1.69

** $p < 0.01$; *** $p < 0.001$.

5.2.2 Walking speed. The mean time series of walking speed for both target trajectories appear in figure 13. The mean initial speed when the target appeared was 1.10 m s^{-1} , and it gradually increased for most of the trial to a mean maximum of 1.42 m s^{-1} , before decreasing slightly to a mean final speed of 1.31 m s^{-1} . These data are almost identical to those of experiment 2. Although offset angle affected target-heading angle, it did not affect walking speed. Separate ANOVAs for both target trajectory conditions revealed no significant effects of offset angle on walking speed (see table 2).

5.2.3 Path variability. Once again path variability gradually increased and then leveled off toward the end of the trial. The effect of offset angle was not statistically significant in either the Cross or Retreat conditions.

Although offset angle had a significant effect on β , it was in the direction opposite that predicted by global optic flow. This result appears to be consistent with reliance on egocentric direction, with the qualification that the motion of the background influenced the perception of the target motion. For example, to produce a negative offset, the room was moved in the same direction as the target, thereby decreasing their relative motion. This may have increased the latency to detect target motion at the onset of a trial, and/or decreased perceived target speed. Conversely, to produce a positive offset, the room was moved in the opposite direction of the target, increasing their relative motion. However, the asymmetry of the offset-angle effect suggests that the increase in relative motion did not decrease the latency to detect target motion.

This interpretation is consistent with the Room effect observed in experiment 1. In that case, removal of the stationary background eliminated relative motion between the target and background. This may have similarly increased the latency to detect target motion and/or reduced the perceived target speed, resulting in a smaller target-heading angle. In sum, the results of experiment 3 are consistent with reliance on egocentric direction rather than global optic flow to guide an interception strategy, and

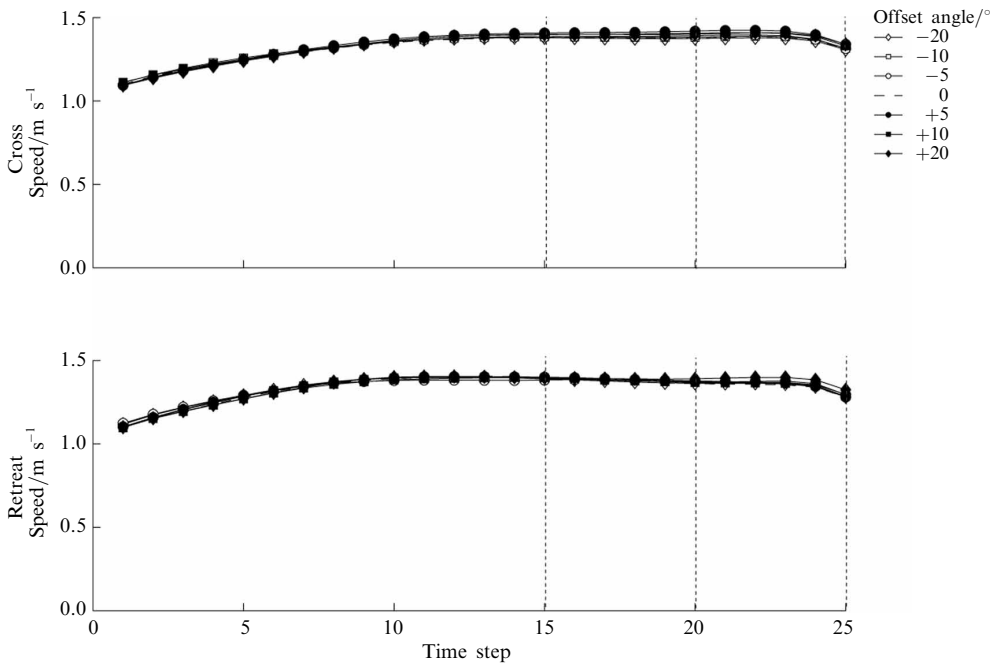


Figure 13. Mean time series of walking speed in the Cross (top panel) and Retreat (bottom panel) conditions of experiment 3. Curves correspond to different offset angle conditions.

suggest that the influence of the background is to enhance or reduce the perceived motion of the target.

6 Experiment 4: Relative motion

We tested the above interpretation in experiment 4 by manipulating the relative motion between the target and the background. In the previous Room condition, the relative motion coincided with target motion, and in the No Room condition relative motion was absent. In the present experiment we added a Moving Room condition in which the background moved at the same speed and direction as the target, thereby reducing the amount of motion parallax between the target and the background. If relative motion between the target and the background influences the detection of target motion, then behavior in the Moving Room condition should be shifted away from that in the Room condition toward that in the No Room condition.

6.1 Method

6.1.1 Participants. Nine undergraduate and graduate students participated in experiment 4. None reported any visual or motor impairment. They were paid \$8 for their participation.

6.1.2 Displays. Displays were similar to those in the Center/Line and Side/Line conditions of experiment 1. The target line appeared at a distance of 4 m along the z axis and traveled on the Cross (0°) or Retreat (30°) trajectory. In the No Room condition, the target appeared in empty black space. In the Stationary Room condition, a room with dimensions 12 m (deep) \times 12 m (wide) \times 2.5 m (high) appeared at the same time as the target. The rear wall of the room was 2 m behind the observer at the time that the target and room appeared. In the Moving Room condition, the room moved at the same speed and direction as the target. As in experiment 1, participants began walking when the red inter-trial markers turned green, the markers disappeared at 0.5 m, and the target appeared at 1.0 m. If the target moved 6 m from the center of the room before the observer reached it, the target disappeared and the trial ended.

6.1.3 *Design.* The design for experiment 4 was 3 (background) \times 2 (target trajectory) \times 2 (center/side location) \times 2 (left/right motion). All variables were within-participants and trials were presented in a completely random order. There were 5 repetitions per condition for a total of 120 trials.

6.2 Results and discussion

6.2.1 *Target-heading angle.* The mean time series of target-heading angle for each condition is shown in figure 14. β reached lower values in the No Room condition than in the Stationary Room condition, replicating the background effect of experiment 1. The new result is that β was also lower in the Moving Room condition than in the Stationary Room condition, shifted in the direction of the No Room condition. This indicates that canceling the relative motion between the target and background influences behavior in the expected direction. Separate ANOVAs for each target trajectory and starting location condition revealed significant main effects of background (see table 3). We also conducted planned comparisons to test the difference between the Stationary and Moving Room conditions at the 25th time step. These differences were significant in the Retreat/Side condition and marginally significant ($p = 0.09$) in the Retreat/Center condition, but did not reach significance in either Cross condition. It could be that this effect was stronger in the Retreat condition because there was more time for the background motion to influence walking direction.

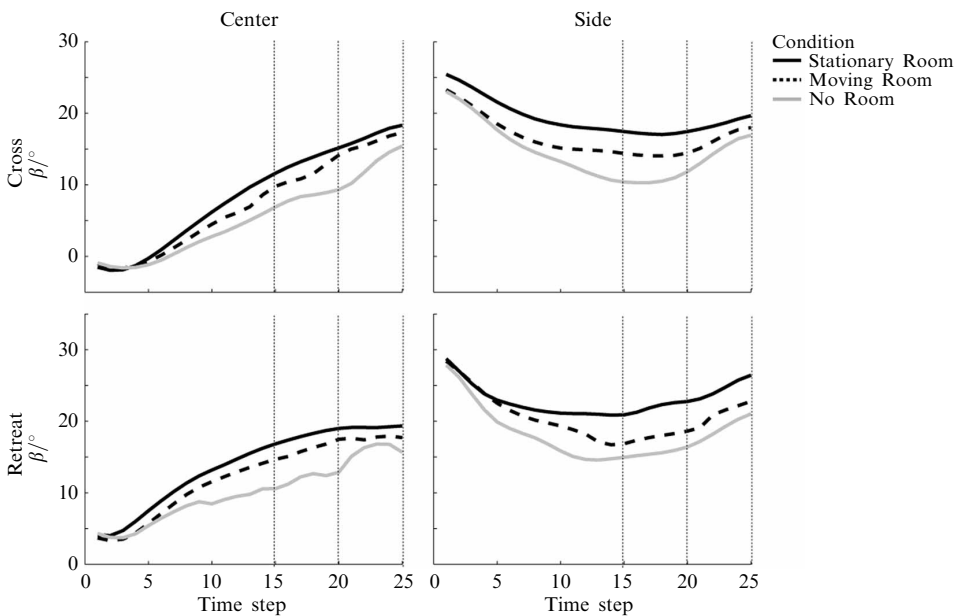


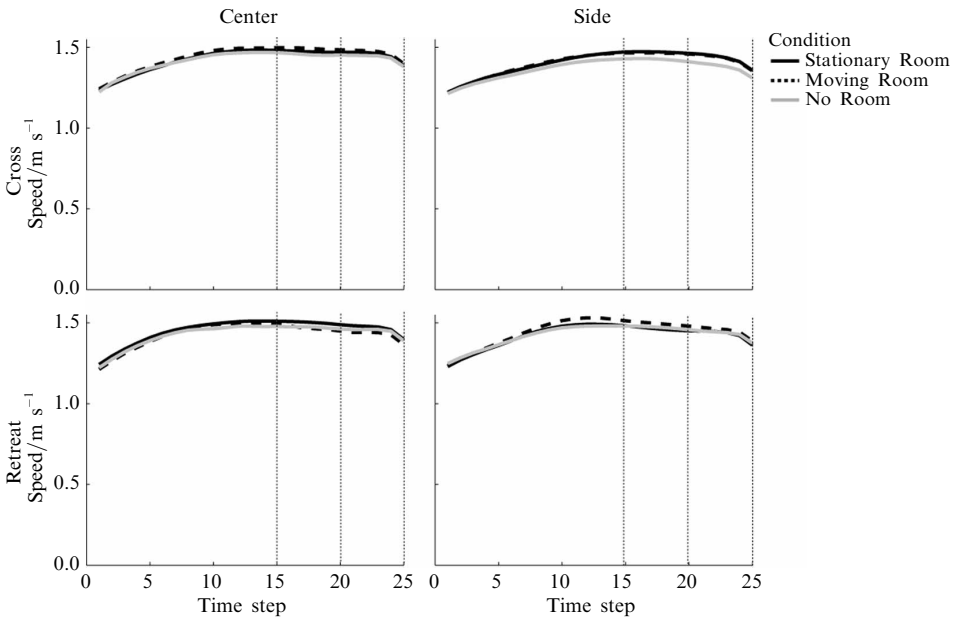
Figure 14. Mean time series of target-heading angle for the initial target locations (Center or Side) and trajectories (Cross or Retreat) of experiment 4. The solid black, solid gray, and dotted black lines correspond to the Stationary Room, No Room, and Moving Room conditions, respectively.

6.2.2 *Walking speed.* Mean time series of walking speed appear in figure 15. The mean initial walking speed at the moment that the target first appeared was 1.23 m s^{-1} , then it gradually increased for most of the trial to a mean maximum value of 1.51 m s^{-1} , before decreasing to a mean final speed of 1.37 m s^{-1} . Separate ANOVAs confirmed that there were no significant main effects or interactions involving background on walking speed (see table 3).

Table 3. *F*-values for ANOVAs in experiment 4.

	Center		Side	
	Cross	Retreat	Cross	Retreat
Target angle, β				
Background	8.70*	9.41**	10.15**	12.78***
Time	41.09***	11.96**	6.51*	8.65*
Background \times Time	2.10	1.78	5.61*	0.26
Walking speed				
Background	0.92	0.68	3.51	0.98
Time	18.92***	28.32***	21.92***	25.13***
Background \times Time	0.50	1.76	0.18	1.20

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

**Figure 15.** Mean time series of walking speed for the initial target locations (Center or Side) and trajectories (Cross or Retreat) in experiment 4. The solid black, solid gray, and dotted black lines correspond to the Stationary Room, No Room, and Moving Room conditions, respectively.

6.2.3 *Path variability.* As in experiment 1, there was a trend toward more variability in the No Room condition compared to the Stationary Room condition. However, the effect of background was not significant in any of the conditions.

Thus, the results are consistent with the interpretation that participants rely on egocentric direction to intercept the target, and the contribution of the background is to enhance or reduce perceived target motion. If so, the question arises why the Moving Room condition did not reduce β to the same level as the No Room condition, given the absence of relative motion in both. It is possible that it is harder to detect the egocentric motion of a single line in empty space than the motion of a large structured scene, which is in turn harder to detect than the motion of a target against a background. This would account for the ordering of conditions in the present data (figure 14).

7 General discussion

The purpose of the present study was to identify the behavioral strategies and visual information used in walking to a moving target. We considered two possible strategies: (a) the pursuit strategy, in which the agent continually heads directly toward the target ($\beta = 0$); and (b) the interception strategy, in which the agent walks ahead of the target ($\beta > 0$). Either strategy may rely upon several types of normally redundant information: (a) egocentric direction, the visual direction of the target relative to the felt locomotor axis; (b) global optic flow, the visual direction of the target relative to the heading specified by the background flow; and (c) local optic flow, the motion pattern from the target itself, which specifies the observer's heading with respect to the target. The experimental results lead us to conclude that participants use an interception strategy to walk to a moving target, and are guided primarily by the egocentric direction of the target. Let us discuss these issues in turn.

7.1 Behavioral strategy

First, the results of experiment 1 clearly demonstrate that participants do not use a pursuit strategy, for β is greater than zero for nearly all of a trial. Rather, they adopt a form of interception strategy, turning to walk ahead of the target regardless of its initial position or trajectory. This is not altogether surprising, for a pursuit strategy would require the agent to continually turn to keep the heading direction aligned with the moving target, leading to a longer curved path with a longer duration. In contrast, an interception strategy leads to a shorter, straighter path to the target. Our finding is contrary to that of Rushton et al (1998), who reported a pursuit strategy with a slowly moving target (0.1 m s^{-1}), which we attribute to our faster suprathreshold target motion (0.6 m s^{-1}). However, it is also contrary to an idealized constant bearing strategy, for participants do not maintain a constant interception angle or follow a straight path, at least over these short distances (3–5 m). Instead, interception behavior exhibits dynamics that include an initial turn onto a straight path with a heading that leads the target, and a final decrease in β at the end of the approach.

In a companion modeling study (Warren and Fajen, submitted), we succeeded in simulating these behavioral dynamics with an extension of our previous model of steering and obstacle avoidance (Fajen and Warren 2003). The basic model is a second-order dynamical system analogous to an angular mass-spring that generates a sequence of headings, assuming a constant walking speed. To steer toward a stationary goal, the model nulls the heading error β , so the heading direction is attracted toward the direction of the goal, at a rate that depends upon target distance. A damping term prevents oscillation about the goal direction and tends to yield straight paths. To model interception, we simply substituted $\dot{\beta}$ for β . The model then nulls $\dot{\beta}$, leading to a constant interception angle, while the damping term leads to a straight path. This yields interception behavior that closely fits the human data in figure 4, including the initial transient to turn ahead of the target depending on initial conditions. The null $\dot{\beta}$ model is similar to one proposed by Wilkie and Wann (2003) for steering to stationary goals, following Fajen and Warren (2003).

7.1.1 Stationary versus moving targets. The finding that people appear to use a pursuit strategy for stationary or slowly moving targets (null β) and an interception strategy for faster moving targets (null $\dot{\beta}$) raises an important question about the organization of behavior. As target speed increases, is there a switch between two distinct strategies? One possibility is that people switch from a null- β strategy for targets that they perceive as stationary to a null- $\dot{\beta}$ strategy for targets that they perceive as moving, as implied in our model. Alternatively, there may be a single strategy that applies to both cases. For example, Wilkie and Wann's (2003) model, which steers to stationary targets by nulling $\dot{\beta}$, would generalize to moving targets. However, Fajen and Warren's (2003)

model, which nulls β , more closely fits the human data for stationary targets across a range of target distances. Another approach is to explicitly compute the interception angle $\hat{\beta}$ [as in equation (1)], which smoothly goes to zero as the target velocity goes to zero, and null $\beta - \hat{\beta}$ (Warren and Fajen, submitted). It remains to be determined whether humans use a single strategy to steer to stationary and moving targets, or whether they switch between two distinct strategies.

7.2 Information

Second, the results indicate that participants rely on the egocentric direction of the moving target to guide their interception behavior, rather than local or global optic flow. In experiment 2, we manipulated the local optic flow from the target independently of egocentric direction and found that participants were unaffected by local optic flow. In experiment 3, we manipulated global optic flow independently of egocentric direction. Although there was an effect of background motion, the direction of the effect was opposite to that predicted by reliance on global optic flow. We hypothesized that relative motion between the target and background can either enhance or reduce the perceived target motion. Converging evidence was provided by experiment 4, in which moving the background at the same speed and direction as the target reduced the target-heading angle. These results lead us to conclude that people walk to moving targets by using an interception strategy based on the egocentric direction of the target, with the caveat that relative motion with the background can influence perceived target motion.

7.2.1 Influence of the background. There is considerable disagreement in the literature over the effects of background structure on perceived speed of a moving object (Gogel and McNulty 1983) and performance on interception tasks such as catching a ball (Savelsbergh and Whiting 1988; Montagne and Laurent 1994; van der Kamp et al 1997), and striking a moving target with the hand (Smeets and Brenner 1995). One of the few consistent findings is that the presence of stationary background texture increases the perceived speed of a moving object. Lenoir et al (1999b) reported precisely this effect for intercepting a moving ball during self-motion. This is consistent with the interpretation that our participants perceived the target speed to be faster when the background was present, and slower when it was absent or moving in the same direction as the target. In addition, the initial detection of target motion at the onset of a trial could have been facilitated by a stationary background, and delayed when the background was absent or moving with the target. Thus, we believe that the influence of the background on perceived target motion is sufficient to account for the observed room effects.

7.2.2 Stationary versus moving targets. Previous research indicates that people use both global optic flow and egocentric direction to walk to a stationary target (Wood et al 2000; Harris and Carré 2001; Warren et al 2001), whereas we find they rely on egocentric direction alone to intercept a moving target. Why might this be so? With a stationary target, the observer can null β by placing the perceived heading on the target, or by canceling the motion parallax of the surrounding environment with respect to the target. If the target is moving, however, the motion parallax cannot be cancelled, and using global optic flow in this manner leads to a pursuit strategy. Thus, global optic flow may dominate with a stationary target when it is particularly effective for nulling β , whereas egocentric direction may dominate with a moving target.

This finding appears inconsistent with the results of Cutting et al (1995), who concluded that collision judgments are based on the motion parallax between the foreground and background of a moving target. However, because they tested a psychophysical task with stationary participants, the proprioceptive locomotor axis was undefined and egocentric direction information was unavailable. Their results thus

demonstrate that the visual system can use the global retinal flow to judge a collision course in the absence of egocentric information. However, our results indicate that actual interception behavior seems to be based on the egocentric direction of the target.

In conclusion, the present results indicate that people walk to moving targets using an interception strategy, that is guided by the egocentric direction of the target. The experiments are part of a research program in which we are testing elementary locomotor behaviors with the aim of modeling locomotion in a complex, dynamic environment.

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References

- Chapman S, 1968 "Catching a baseball" *American Journal of Physics* **53** 849–855
- Chardenon A, Montagne G, Buekers M J, Laurent M, 2002 "The visual control of ball interception during human locomotion" *Neuroscience Letters* **334** 13–16
- Cutting J E, Vishton P M, Braren P A, 1995 "How we avoid collisions with stationary and with moving obstacles" *Psychological Review* **102** 627–651
- Fajen B R, Warren W H, 2003 "Behavioral dynamics of steering, obstacle avoidance, and route selection" *Journal of Experimental Psychology: Human Perception and Performance* **29** 343–362
- Gibson J J, 1950 *Perception of the Visual World* (Boston, MA: Houghton Mifflin)
- Gibson J J, 1958/1998 "Visually controlled locomotion and visual orientation in animals" *British Journal of Psychology* **49** 182–194 (Reprinted in *Ecological Psychology* **10** 161–176)
- Gogel W C, McNulty P, 1983 "Perceived velocity as a function of reference mark density" *Scandinavian Journal of Psychology* **24** 257–265
- Harris J M, Bonas W, 2002 "Optic flow and scene structure do not always contribute to the control of human walking" *Vision Research* **42** 1619–1626
- Harris M G, Carré G, 2001 "Is optic flow used to guide walking while wearing a displacing prism?" *Perception* **30** 811–818
- Kamp J van der, Savelsbergh G J P, Whiting H T A, Smeets J B J, 1997 "Multiple information sources in interceptive timing" *Human Movement Science* **16** 787–821
- Kim N-G, Turvey M T, 1999 "Eye movements and a rule for perceiving direction of heading" *Ecological Psychology* **11** 233–248
- Lanchester B S, Mark R F, 1975 "Pursuit and prediction in the tracking of moving food by teleost fish" *Journal of Experimental Biology* **63** 627–645
- Landy M S, Maloney L T, Johnston E B, Young M, 1995 "Measurement and modeling of depth cue combinations: In defense of weak fusion" *Vision Research* **35** 389–412
- Lee D N, 1998 "Guiding movement by coupling taus" *Ecological Psychology* **10** 221–250
- Lenoir M, Musch E, Janssens M, Thiery E, Uyttenhove J, 1999a "Intercepting moving objects during self-motion" *Journal of Motor Behavior* **31** 55–67
- Lenoir M, Savelsbergh G J, Musch E, Thiery E, Uyttenhove J, Janssens M, 1999b "Intercepting moving objects during self-motion: Effects of environmental changes" *Research Quarterly in Exercise and Sport* **70** 349–360
- Li L, Warren W H, 2000 "Perception of heading during rotation: Sufficiency of dense motion parallax and reference objects" *Vision Research* **40** 3873–3894
- Michaels C F, Oudejans R D, 1992 "The optics and actions of catching fly balls: Zeroing out optical acceleration" *Ecological Psychology* **4** 199–222
- Montagne G, Laurent M, 1994 "The effects of environmental changes on one-handed catching" *Journal of Motor Behavior* **26** 237–246
- Regan D, 1993 "Binocular correlates of the direction of motion in depth" *Vision Research* **33** 2359–2360
- Rogers B J, Allison R S, 1999 "When do we use optic flow and when do we use perceived direction to control locomotion?" *Perception* **28** Supplement, 2
- Royden C S, Crowell J A, Banks M S, 1994 "Estimating heading during eye movements" *Vision Research* **34** 3197–3214
- Rushton S K, Harris J M, Lloyd M, Wann J P, 1998 "Guidance of locomotion on foot uses perceived target location rather than optic flow" *Current Biology* **8** 1191–1194
- Savelsbergh G J P, Whiting H T A, 1988 "The effect of skill level, external frame of reference, and environmental changes on one-handed catching" *Ergonomics* **31** 1655–1663
- Smeets J B J, Brenner E, 1995 "Perception and action are based on the same visual information: Distinction between position and velocity" *Journal of Experimental Psychology: Human Perception and Performance* **21** 19–31

-
- Telford L, Howard I P, Ohmi M, 1995 “Heading judgments during active and passive self-motion” *Experimental Brain Research* **104** 502–510
- Wann J P, Edgar P, Blair D, 1993 “Time-to-contact judgment in the locomotion of adults and preschool children” *Journal of Experimental Psychology: Human Perception and Performance* **19** 1053–1065
- Wann J P, Swapp D K, 2000 “Why you should look where you are going” *Nature Neuroscience* **3** 647–648
- Warren W H, 2003 “Optic flow”, in *The Visual Neurosciences* Eds L M Chalupa, J S Werner (Cambridge, MA: MIT Press) pp 1247–1259
- Warren W H, Fajen B R, in press “From optic flow to laws of control”, in *Optic Flow and Beyond* Eds L Vaina, S K Rushton, S Beardsley (Dordrecht: Kluwer) pp 307–337
- Warren W H, Fajen B R, submitted “Behavioral dynamics of intercepting a moving target on foot” *Experimental Brain Research*
- Warren W H, Kay B A, Zosh W D, Duchon A P, Sahuc S, 2001 “Optic flow is used to control human walking” *Nature Neuroscience* **4** 213–216
- Warren W H, Saunders J A, 1995 “Perceiving heading in the presence of moving objects” *Perception* **24** 315–331
- Wilkie R M, Wann J P, 2002 “Driving as night falls: The contribution of retinal flow and visual direction to the control of steering” *Current Biology* **12** 2014–2017
- Wilkie R M, Wann J P, 2003 “Controlling steering and judging heading: Retinal flow, visual direction, and extra-retinal information” *Journal of Experimental Psychology: Human Perception and Performance* **29** 363–378
- Wood R M, Harvey M A, Young C E, Beedie A, Wilson T, 2000 “Weighting to go with the flow?” *Current Biology* **10** R545–R546

APPENDIX: Interception

Target velocity u can be described by two orthogonal components, the transverse speed u_t perpendicular to the agent's line of sight, and the radial speed u_r along the line of sight (figure 1c). Analogously, agent velocity v has a transverse component v_t and a radial component v_r . If the following two conditions are satisfied, the agent will successfully intercept the target.

(1) First, the agent matches the transverse speed of the target

$$v_t = u_t . \quad (\text{A1})$$

They thus share a common moving reference frame, reducing the problem to one dimension.

(2) All that remains is that the agent move toward the target along the line of sight:

$$v_r > u_r \quad (\text{A2})$$

so the target (or goal) distance d_g decreases.

If u and v are constant, these conditions result in a straight path with a constant interception angle, that intercepts the target at the point where the two paths cross. The first condition guarantees that the agent and target (goal) will arrive at the interception point at the same time ($t_a = t_g$). Since

$$\begin{aligned} t_a &= d_t / v_t , \\ t_g &= d_t / u_t ; \end{aligned} \quad (\text{A3})$$

then if $v_t = u_t$ they will travel the same transverse distance d_t in the same amount of time, $t_a = t_g$. (Equal time intervals are indicated by the parallel dotted lines in figure 1c.) The second condition guarantees that the two paths intersect. On the other hand, if $v_r = u_r$ they are parallel, and if $v_r < u_r$ they diverge, so interception is unsuccessful.

For a given agent speed $\|v\|$, the required interception angle $\hat{\beta}$ that will yield a straight path at a constant angle follows from the first condition

$$\hat{\beta} = \arcsin\left(\frac{v_t}{\|v\|}\right) = \arcsin\left(\frac{u_t}{\|v\|}\right) . \quad (\text{A4})$$

Conversely, for a given interception angle, the required agent speed is

$$\|v\| = \frac{u_t}{\sin \hat{\beta}} . \quad (\text{A5})$$

If agent speed $\|v\|$ or target speed, or direction u change during the approach, then the path may not be straight and $\hat{\beta}$ may not be constant. However, as long as the two conditions continue to be satisfied, such that the agent tracks the change in u and keeps closing the target distance, interception will eventually succeed.

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