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Baseball Outfielders Maintain a Linear Optical Trajectory When Tracking Uncatchable Fly Balls

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The authors investigated whether behavior of fielders pursuing uncatchable fly balls supported either (a) maintenance of a linear optical trajectory (LOT) with monotonic increases in optical ball height or (b) maintenance of optical acceleration cancellation (OAC) with simultaneous lateral alignment with the ball. Past work supports usage of both LOT and OAC strategies in the pursuit of catchable balls headed to the side. When balls are uncatchable, fielders must choose either optical linearity or alignment at the expense of the other. Fielders maintained the LOT strategy more often and for a longer period of time than they did the OAC alignment strategy. Findings support the LOT strategy as primary when pursuing balls headed to the side, whether catchable or not.

The phenomenon of how skilled outfielders can get to exactly the right spot at the right time to catch a ball has been called the *outfielder problem* (Chapman, 1968; Dienes & McLeod, 1993; McBeath, 1990; McLeod & Dienes, 1993, 1996; Montagne, Laurent, & Durey, 1998; Oudejans, Michaels, Bakker, & Davids, 1999; Todd, 1981). The ball is initially distant enough so that the major depth cues are inoperable (e.g., stereo, accommodation, and size change, or *tau*, all are absent). These cues are used near the end of the trajectory to make final adjustments (Kaiser & Mowafy, 1993; Lee, 1976; Peper, Bootsma, Mestre, & Bakker, 1994; Savelsbergh, Whiting, & Bootsma, 1991; Tresilian, 1990). Other factors that are important only in the final stages of catching include making judgments about when to initiate a grasping response (Alderson, Sully, & Sully, 1974; Savelsbergh & Whiting, 1988; Weiss & Jeannerod, 1998) and the signaling of kinesthetic information by peripheral receptors (Peper et al., 1994). Thus, the principal cues used to solve the outfielder problem are limited to temporal and spatial changes in the optical trajectory of the ball.

The Optical Acceleration Cancellation Model

Chapman (1968) was the first to propose an optical strategy of how baseball outfielders approach fly balls. Figure 1 shows side views of three trajectories of baseballs headed in the plane straight toward the outfielder (ignoring the effects of air resistance and ball spin): (a) standing at the correct ball destination, (b) moving forward at a constant speed toward the ball destination, and (c) moving backward at a constant speed toward the ball destination. Chapman noted that in cases in which the fielder is stationary or running in the correct linear, constant-velocity path to the ball destination, the tangent of the vertical optical angle, tanα, increases at a constant rate. This is shown geometrically in Figure 1 by the constant intervals along the dotted line rising from home plate. Chapman was the first to note that a fielder can converge on the ball by running along a path in which the ball optically continues to rise throughout its trajectory. As shown in Figure 1, the optical ball trajectory is like that of an imaginary elevator rising from home plate at constant velocity and tilted by the amount that the fielder runs forward or backward.

Chapman (1968) and others (Babler & Dannemiller, 1993; McLeod & Dienes, 1993; Michaels & Oudejans, 1992) have suggested that outfielders catch fly balls by using principally temporal aspects or acceleration of the optical trajectory. McLeod and Dienes (1993, 1996) have confirmed that fielders maintain optical acceleration cancellation (OAC) under conditions with real balls headed in the plane directly toward them. As the ball rises, tanα increases at a rate that is a function of the running path selected. The fielder can arrive at the correct destination by selecting a running path that keeps optical ball speed constant, achieving OAC of tanα. If the fielder runs too far in (so that the ball will land behind him), $d(\tan\alpha)/dt$ will increase. If the fielder does not run in far enough, $d(\tan\alpha)/dt$ will decrease. When the fielder continually adjusts his or her running path to maintain a constant $d(\tan\alpha)/dt$, he or she will converge to the correct destination.

McLeod and Dienes (1993, 1996) have demonstrated that fielders maintain OAC under conditions with real balls headed in the sagittal plane directly toward them. For balls not headed directly at fielders, Chapman (1968) has suggested that the fielders select a running path that maintains a constant change in the tangent of the vertical optical angle, tanα, while also maintaining lateral align-

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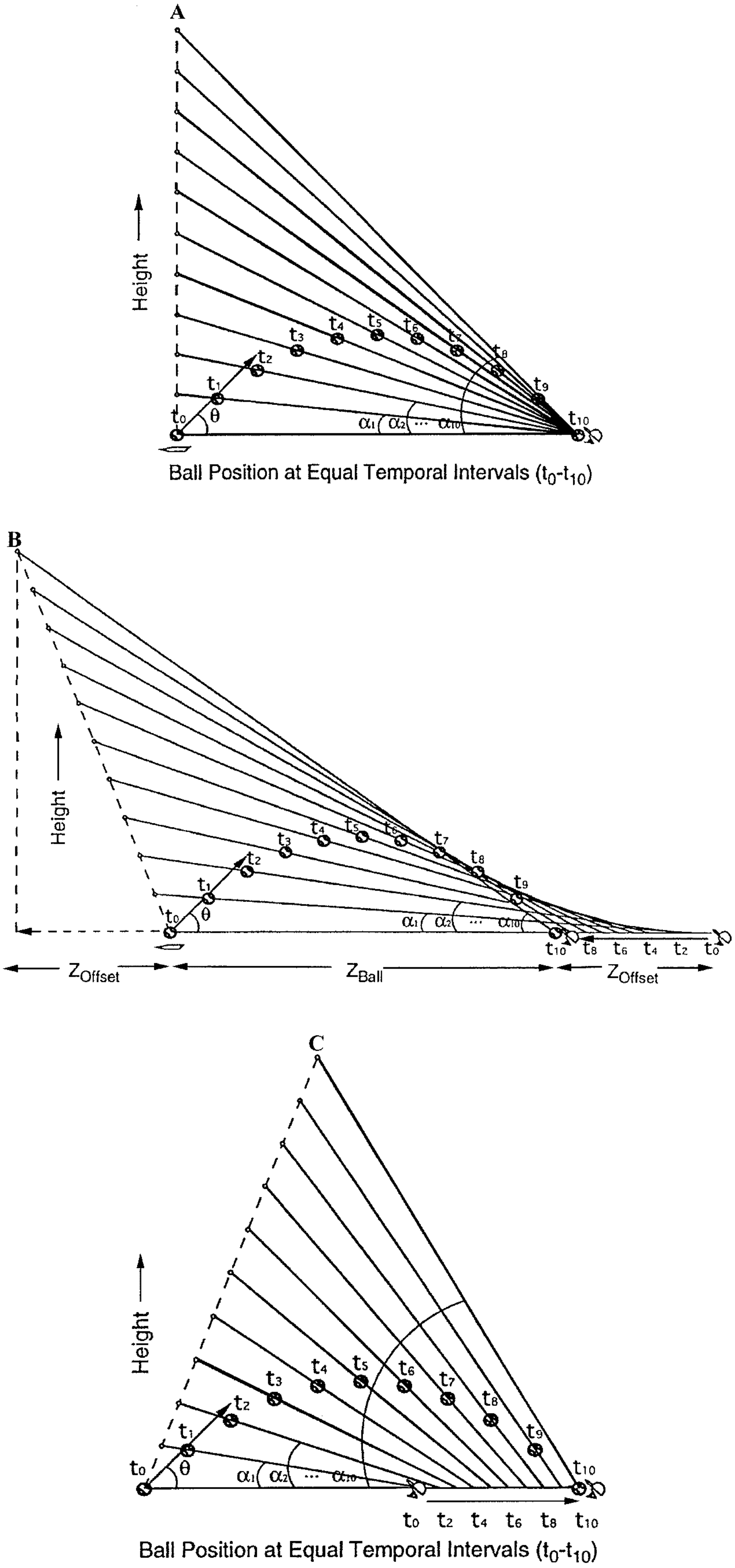
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ment with the ball. Essentially, they perform OAC in the depth direction while laterally staying aligned with the ball. Since Chapman, researchers have described more sophisticated versions of OAC nulling models that account for ball trajectories that deviate from the parabolic ideal due to air resistance (e.g., McLeod & Dienes, 1996). Furthermore, only the sign of acceleration needs to be detected to intercept the ball when it remains in the sagittal plane of the fielder (Tresilian, 1995). Yet, even these more sophisticated models typically either do not address the issue of balls headed off to the side or presume maintenance of lateral alignment.

The OAC model is a mathematically elegant description of how outfielders catch fly balls, and there is empirical support for it in cases of balls headed straight toward the outfielder (Babler & Dannemiller, 1993; McLeod & Dienes, 1993, 1996). However, OAC has some weaknesses as a principal control variable when balls are headed off to the side. McBeath, Shaffer, and Kaiser (1995a, 1995b, 1996) have indicated some of these weaknesses in articles introducing an alternative model of how baseball outfielders determine where to run to catch fly balls, and we briefly describe them here.

First, the OAC alignment strategy assumes that viewers are very good at discriminating rates of acceleration, but laboratory evidence suggests otherwise (Calderone & Kaiser, 1989; Gottsdanker, 1956; Gottsdanker, Frick, & Lockard, 1961; Jagacinski, Burke, & Miller, 1977; Regan, Kaufman, & Lincoln, 1986; Runeson, 1974, 1975; Schmerler, 1976; Todd, 1981; Werkhoven, Snippe, & Toet, 1992; cf. Babler & Dannemiller, 1993). In general, both acceleration and deceleration are difficult to perceive. For an acceleration change to be detected only 50% of the time in laboratory settings, it typically takes an increase or decrease in velocity of between 80% and 320% (Calderone & Kaiser, 1989; Schmerler, 1976; Todd, 1981). Tresilian (1995) has shown that observers' abilities to discriminate whether a stimulus is accelerating or decelerating is sufficient for them to intercept balls projected in the sagittal plane toward them. However, when balls are also headed somewhat to the side, performance accuracy largely breaks down. In this case, Tresilian (1995) suggests that an additional control action like lateral alignment is needed to null out the horizontal velocity of the ball's image. Our work suggests that fielders do not necessarily maintain lateral alignment when pursuing balls headed to the side (McBeath et al., 1995a).

Second, OAC utilizes the tangent of the vertical optical angle, $\tan\alpha$, as the optical invariant rather than the optical angle, α, itself. Although these two variables, $\tan\alpha$ and α, are equivalent in the region where the law of small angles holds, they diverge markedly at the large αs found for high fly balls. For example, Jacobs, Lawrence, Hong, Giordano, and Giordano (1996) described high pop-ups that approach optical angles of 70°. In such cases, a constant rate of change in $\tan\alpha$ produces a change in the actual optical angle, α, that slows down to nearly one tenth of the initial optical velocity. It seems unlikely that observers would experience such dramatic decreases in optical ball speed to be constant, although they do behave in a way that maintains constancy of the change in $\tan\alpha$. Because most studies on velocity and acceleration perception use limited-angle electronic displays, they operate in the region where the law of small angles holds and substitutions of $\tan\alpha$ for α are transparent.

Third, the OAC strategy alone does not include a mechanism for navigating laterally. Most work testing the OAC model includes only balls directed in the sagittal plane toward the fielder. Researchers typically suggest that for balls headed to the side, fielders perform the same OAC mechanism while maintaining lateral alignment (Chapman, 1968; Dannemiller, Babler, & Babler, 1996). The concept of maintaining lateral alignment is questionable because it assumes that the fielder has access to a world-based coordinate system with a euclidean orthographic projection of the field. Actually, the fielder has a viewer-based coordinate system with a spherical optical projection. A spherical projection provides only optical angular information and would require an accurate representation of distances to the ball and background scenery to reliably define and indicate lateral alignment. Because these distances are not assumed to be known by the fielder, there is no way of determining the extent of perspective foreshortening that specifies lateral alignment with the approaching ball (McBeath et al., 1995a).

Fourth, if the OAC strategy uses an independent method to achieve lateral convergence toward balls headed to the side, then these cases would be expected to be more computationally complex and difficult to catch than balls headed in the plane directly toward the fielder. In these cases, the fielder must simultaneously maintain both a constant increase in $\tan\alpha$ and lateral alignment, as shown in Figure 2. Presumably, the additional task of maintaining alignment will make balls headed to the side more difficult to catch. Yet fielders commonly report the opposite (Shaffer & McBeath, 1997).

Fifth, much of the research examining fielder behavior and tests of OAC rely on indirectly modeling the optical ball trajectory on the basis of external measurements of the location of the fielder and the ball. This methodology has a potential weakness in that it may introduce error in the position of either the ball or the fielder. In contrast, researchers can eliminate these potential sources of error by directly measuring the optical ball path with a camera from the perspective of the moving fielder (Marken, 1997).

When fielders successfully catch balls, what is occurring optically is consistent with cancellation of optical acceleration, but it may be operating in parallel with another control heuristic that is primary (McBeath et al., 1995a, 1996). Virtually all studies have examined only cases of successful catches. In these cases, the

Figure 1 (*opposite*). The optical acceleration cancellation (OAC) alignment model: The OAC alignment model specifies that outfielders catch fly balls by running along a path that vertically maintains constant optical ball velocity and horizontally maintains alignment with the ball. Shown are side views of cases with the ball traveling through a parabolic trajectory (i.e., ignoring the effects of ball spin and air resistance). Ball and fielder positions are indicated at times t_0, initiation, through t_{10}, the point of catch. A: Case of a stationary observer standing at the destination point. B: Case of an observer running up to catch the ball. C: Case of an observer running back to catch the ball.

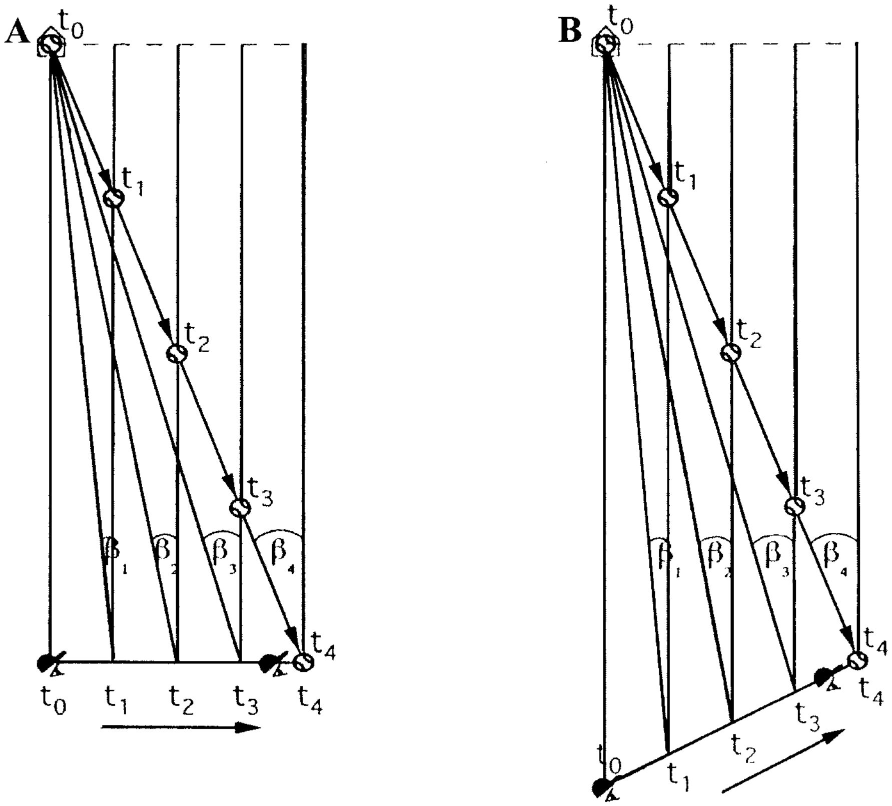

Figure 2. Top or bird's eye view of an outfielder running to catch a ball. A: When balls are headed directly off to the side of the fielder, the optical acceleration cancellation alignment model specifies that the fielder maintains lateral alignment with the ball at each point in time. When this happens, the tangent of the lateral optical angle, β, increases linearly. B: When fielder offset is both lateral and in depth and alignment with the ball is maintained, the tangent of β increases at an accelerating rate (e.g., here, β_1 is smaller in B than in A, but β_4 is the same in each). t = time.

optical trajectory may have geometric constraints that tend to lead to a relatively constant optical ball velocity independent of whether optical acceleration is being used by the fielder as the principal control variable by the fielder (Michaels & Ouedejans, 1992).

The Linear Optical Trajectory Model

In our previous work, we found evidence supporting that the optical information available to the outfielder can be simply analyzed without breaking it down into separate vertical and horizontal components, but instead examining it as a unified 2-D optical image (McBeath et al., 1995a). The geometry of the unified 2-D optical image is shown in Figure 3A, where α and β, respectively, specify the vertical and lateral optical angles between the ball and its initial optical location (home plate). Ψ specifies the optical trajectory projection angle, or the observed angle of ball movement in the picture plane relative to the background horizon. In short, a linear optical trajectory (LOT) results when the fielder's running speed and direction maintain a rate of change in the horizontal optical angle, β, that matches the rate of change in the vertical optical angle, α. This is equivalent to maintaining a constant angle of the ball in the picture plane, Ψ, as shown in Figure 3B. The optical projection angle, Ψ, is the angle of the moving image of the ball, relative to background scenery, that can be recorded on a video camera held by a fielder while he or she runs to make a catch. To maintain a constant rate of lateral change, as shown in Figure 3B, the outfielder runs fastest laterally at the start, gets a little ahead of the ball, and then eases up somewhat at the end.

The LOT strategy specifies that fielders continuously maintain monotonically increasing vertical and lateral optical angles (McBeath et al., 1995a, 1996). In McBeath et al. (1995a), we outlined a theoretical proof that showed that when projection plane geometry is used, the projection angle, Ψ, will remain constant, provided the vertical and lateral optical tangents increase proportionally. In later work, we and others suggested a more general definition of linearity that could apply to spherical coordinates, which specified that the projection angle, Ψ, remained constant when changes in the vertical and lateral optical angles, α and β, remained proportional (Aboufadel, 1996; McBeath et al., 1996). In keeping with this interpretation, we analyze linearity in our data using plots of α and β and not $\tan\alpha$ and $\tan\beta$.

The LOT strategy provides not a single unique solution, but a family of possible running-path solutions for the same ball trajec-

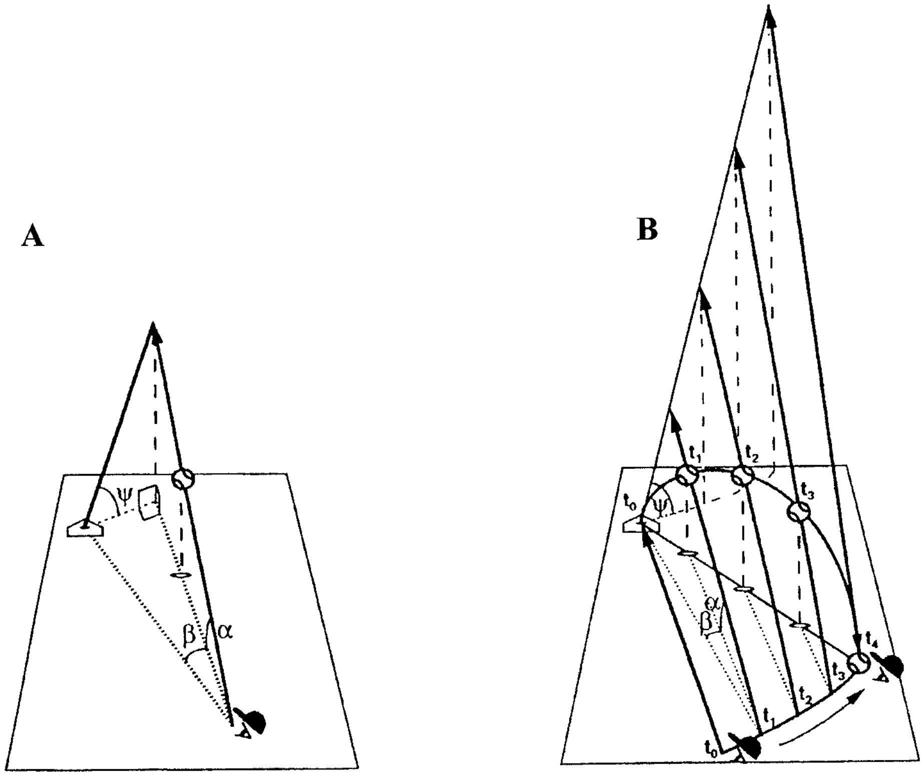

Figure 3. The linear optical trajectory (LOT) model: Centerfield bleacher view of a fielder converging on a ball headed to his or her right. The trapezoidal box represents the perspective projection of the ground plane. The optical trajectory is shown with vectors from the fielder's position through the ball. A: Optical angle definitions: α = vertical optical angle; β = lateral optical angle; Ψ = picture plane optical angle (where $\tan\alpha/\tan\beta = \tan\Psi$, for a planar projection). B: The LOT heuristic of maintaining a constant angle, Ψ, does not demand a unique solution. The fielder selects a running path such that the lateral optical ball movement remains proportional to the vertical optical ball movement. Because equal lateral optical angles span smaller distances for nearer objects, the fielder ends up slowing down laterally as the ball approaches. The resultant running path curves slightly and circles under the ball. t = time.

tory. This strategy works as long as the fielder moves in such a way as to match the rates of increase in the vertical and lateral optical angles and thus keeps the picture plane angle, Ψ, constant. If the optical ball trajectory curves downward, the ball will land in front of the fielder. If the optical trajectory curves upward, the ball will pass over and beyond the fielder. The fielder's task is essentially to discriminate and maintain a straight optical trajectory versus a curved one. As long as the fielder can preserve a monotonically increasing LOT, he or she will maintain control of the ball and will travel to the correct destination. The LOT strategy converts the temporal information of the OAC model to spatial information. If the fielder is running along a path and the optical ball trajectory begins to accelerate vertically, it will manifest itself by curving upward. If the vertical optical trajectory decelerates, it will manifest itself by curving downward. Maintaining a monotonically increasing LOT is, in effect, a spatial method of achieving cancellation of optical acceleration.

The LOT model addresses weaknesses that OAC has as the principal control variable when balls are headed to the side. First, in the LOT model, the task of the fielder is to discriminate a straight trajectory from a curved trajectory rather than to discriminate accelerations. Empirical evidence indicates that observers are very good at curvature discrimination (Cornilleau-Peres & Droulez, 1989, 1992; Foster, Simmons, & Cook, 1993; Hopkins, Kagan, Brachfeld, Hans, & Linn, 1976; Kramer & Fahle, 1996; Norman & Lappin, 1992; Ogilvie & Daicar, 1967; Riggs, 1973; Timney & MacDonald, 1978; Watt & Andrews, 1982). In contrast, it has been shown that observers are generally poorer at discriminating accelerations (e.g., Calderone & Kaiser, 1989; Gottsdanker, 1956; Gottsdanker et al., 1961; Regan et al., 1986; Runeson, 1974, 1975; Schmerler, 1976; Todd, 1981; Werkhoven et al., 1992), although there has been some debate (cf. Babler & Dannemiller, 1993; Dannemiller et al., 1996).

Second, the LOT strategy is based on maintenance of the spatial optical invariant of angular constancy, whereas the OAC model is based on maintenance of the temporal optical invariant of speed constancy. The LOT strategy uses the ratio of optical angles and does not need to address the temporal issue of whether equal changes in $\tan\alpha$ appear constant.

Third, the LOT model does not require that the fielder additionally discern and maintain lateral alignment. That is, the LOT model asserts not that fielders need to independently monitor lateral location of the ball, but rather that they calibrate lateral against vertical movement as a simplifying constraint.

Fourth, fielders commonly report that balls hit to the side are easier to catch than balls hit in the sagittal plane directly at them (Shaffer & McBeath, 1997). The LOT model predicts this because the LOT heuristic functions only when the ball is headed to the side. When it is headed straight toward the fielder, the trajectory is always straight, and the fielder must resort to using only OAC.

Fifth, maintenance of a LOT does not negate OAC, but rather provides an additional complementary control cue for balls headed to the side. Our previous findings show that when directly measuring the relationship between players' movements on the field and the optical trajectory of caught balls, fielders maintain both a LOT and OAC (McBeath et al., 1995a, 1996). Thus, inferences about what is occurring optically may appear to support cancellation of optical acceleration when LOT maintenance may be operating in parallel as the primary control heuristic.

Investigating Outfielder Behavior in Cases of Failure

Essentially all previous studies investigating the process of how outfielders catch fly balls have limited the trials to cases in which the outfielders catch the balls. That work has confirmed that in general, when outfielders catch fly balls headed to the side, they maintain both spatial linearity of the ball (as predicted by the LOT model) and temporal constancy (as predicted by the OAC model). Locomotion that gets the fielder to the right place at the right time will tend to linearize optical ball position regardless of the optical information on which it is actually based (Michaels & Oudejans, 1992). However, in cases in which fielders miss the ball, both the spatial linearity and temporal constancy control strategies must break down. Thus, uncatchable balls can provide a good test case to see which strategy is primary.

The present study was designed to test which optical control strategy outfielders maintain longer: a linear increase in tanα while maintaining lateral alignment (i.e., OAC with alignment) or matching rates of increases in α and β (i.e., LOT). If spatial linearity is used as the principal strategy, then a LOT should be maintained as long as possible and longer than temporal constancy (OAC) with alignment. If a temporal strategy with alignment is used, then spatial linearity should not prevail longer than temporal constancy. Differences from the predictions of the two control strategies should also be measurable in the shapes of the running paths that fielders choose. To our knowledge, the present study is the first to systematically examine failure behavior of outfielders.

The present study consists of two experiments. Experiment 1 examines the running paths of fielders pursuing uncatchable balls headed off to the side and tests whether the paths are more consistent with the lateral strategy of OAC alignment or maintenance of a LOT. Experiment 2 examines the optical trajectories of uncatchable balls headed to the side for moving fielders and tests whether the control variable of linearity is maintained significantly longer than that of acceleration cancellation.

Experiment 1

Experiment 1 investigates the running paths and speed of fielders when pursuing uncatchable fly balls. For catchable balls, we have found that fielders scale the amount of lateral relative to vertical optical ball movement (McBeath et al., 1995a). They typically initiate their own movement by running ahead laterally and curving either slightly forward for balls headed in front of them or backward for balls headed behind them. We expect that they will behave similarly for uncatchable balls. When balls are catchable, fielders typically accelerate up to a maximum speed and later slow down. For uncatchable balls, we expect fielders to accelerate up to a maximum speed and maintain that maximum speed until the ball reaches the ground. Figure 4 shows running-path predictions of the LOT and OAC alignment models. The OAC alignment model predicts that for balls headed off to the side, fielders will, to the best of their ability, stay laterally aligned with the ball while running forward or backward, as specified by OAC. This will result in fielders running at top speed just to maintain alignment while heading somewhat forward or backward toward the ball, resulting in a near linear path toward the ball trajectory. When balls are headed to land too far in front of the fielder, the LOT results in a running path that curves out and up toward the

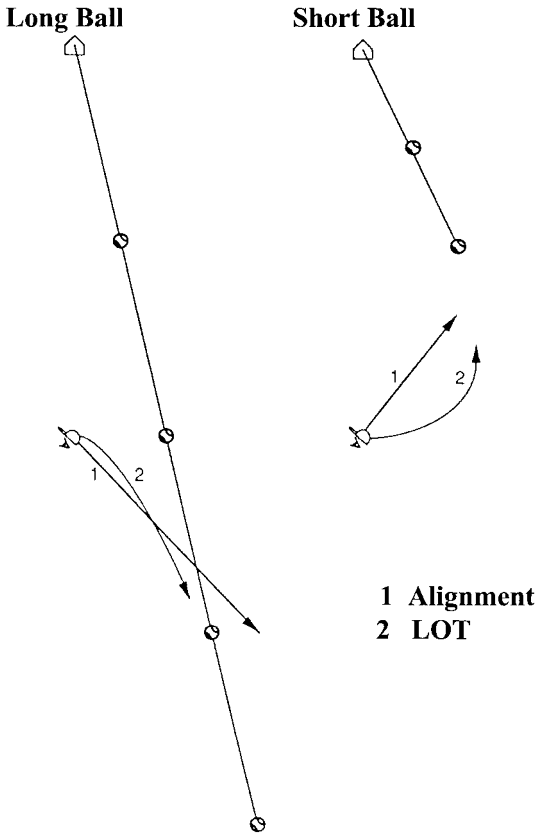

Figure 4. Overhead view of optical acceleration cancellation (OAC) alignment and linear optical trajectory (LOT) running path strategies for long and short balls. The OAC alignment model predicts that fielders will maintain lateral alignment with the ball while running as fast as they can forward or backward toward it. This results in a near linear running path. The LOT model predicts that fielders will maintain a lateral optical ball angle that decreases or increases proportionally to the respective decreasing or increasing vertical optical ball angle. This results in a running path that curves slightly behind and then toward the destination point (for balls headed in front) and curves slightly in front and then back toward the destination point (for balls headed over the fielder's head).

ball, whereas the OAC alignment model predicts that fielders will stay laterally aligned with the ball while running forward, resulting in the running path shown in Figure 4. When balls are headed beyond the fielder, the LOT results in a running path that curves out and back toward the ball, whereas OAC alignment results in a path that places the running fielder perfectly aligned underneath the ball as it passes overhead. Both models predict that fielders will quickly accelerate to maximum speed and maintain that maximum speed. Experiment 1 was done to test whether fielders (a) run primarily along a path that curves in the direction predicted by the LOT model or (b) run primarily along a path that is straight and maintains lateral alignment as much as possible, as predicted by the OAC alignment model (Dannemiller et al., 1996).

Method

Subjects. Five skilled (but not professional quality) outfielders pursued fly balls. All fielders were male and had extensive experience playing outfield in recreational softball. In keeping with our efforts to concentrate on within-subjects consistency and not on individual differences, we limited our subject pool to 5 skilled fielders.

Apparatus. A video camera mounted on a tower was used to record the running path and speed of outfielders.

Instructions given to fielders. Fielders were told that they were to attempt to catch every ball thrown to them. They were instructed that some balls would be thrown within catching distance and some would not. They were told to go all out and use the best of their ball-catching abilities to get to the ball before it landed. They were explicitly instructed to make sure that their pursuit of the ball did not stop, or even slow down, for any time period until after the ball hit the ground. Fielders were trained with pilot trials and debriefed several times to verify that they were going all out on every trial. We also included occasional catchable balls, so they did not know the outcome ahead of time, and we confirmed their continuous efforts with both self-reports and experimenter observations. The fielders we used were confident enough and fast enough, and balls were launched to land close enough so that the fielders believed that they had a competitive chance of getting to the balls before they hit the ground.

Design and procedure. The locations and order in which catchable and uncatchable balls were launched were randomized to limit anticipation by the fielder for any one type of fly ball. We examined the speed of the fielders in each sequence to verify that they were not stopping early or otherwise failing to pursue the ball with all their effort throughout the entire time the ball was in the air. There were no trials in which the plot of distance by time revealed an inverted-U-shaped function (reaching a peak speed and then slowing during ball flight).

We recorded 40 independent trial sequences of the running paths and speeds of fielders attempting to catch fly balls that they could not quite catch in the air. Each trial sequence was videotaped using a camera located above and directly behind the fielder. To code the path and speed of the fielder from the videotape, a transparency was made with graphed blocks that divided the field into 198 equal 2-yard × 2-yard (2.2-m × 2.2-m) units. The outfielder's initial position on the field was fixed and marked as the (0, 0) coordinate. The transparency was superimposed over a video monitor, and fielder position was coded at each tenth of a second.

The path was then transformed from trapezoidal to euclidean coordinates to represent undistorted ground position as a function of time. The speed at which the fielder moved while attempting to intercept the ball was calculated by determining change in distance per video frame.

Results

Each running-path trial was compared with the best-fit linear and quadratic (single-curve) functions. We interpreted the path as curved in the predicted direction if the quadratic fit accounted for a significant increase in variance over the linear fit (we used the change-in-R^2 test, $p < .01$) and the direction of curvature had the correct sign. By these criteria, 35 out of 40, or 88%, of the trials were curved in the direction predicted by the LOT model. A sign test was then performed comparing the total of 35 trials in which the running path was curved in the predicted direction with the number of trials that would be expected randomly. Rather than simply assuming that the chance of the fielder running along a significantly curved path was simply 1/100 (i.e., $p = .01$), as specified by the change-in-R^2 test, we made the conservative assumption that really there were only four possible fielder alternatives. The four running-path alternatives were (a) a curved path consistent with the LOT, (b) a straight path consistent with OAC alignment, (c) a path that curved opposite to that predicted by a LOT, and (d) a noisy path that was inconsistent with both straight and curved alternatives. Therefore, we specified the chance probability of selecting a path significantly curved in the direction predicted by LOT as 0.25. A sign test indicated that there were significantly more trials curved in the direction predicted by the LOT model than expected by chance, $z(40) = 9.12$, $p < .001$. Figure 5 shows typical empirical examples of running paths of fielders with balls headed too far behind and too far in front of them. The landing location of the balls for each path is indicated by the same symbol as the running path. The ball location can be distinguished from the last coordinate of the running path as the ball is displaced from it by anywhere from 2.5 to 7 yards (2.3 to 6.4 m). In all trials, fielders accelerated to and maintained full speed, in keeping with instructions.

Experiment 1 established that when fielders attempt to intercept uncatchable balls, their running paths typically curve in a manner that is more consistent with maintaining a LOT than with OAC alignment. Nevertheless, our running-path findings are only an indirect test of optical strategy. It is difficult to account for all possible extraneous variables, such as the effects of air resistance and ball spin, that could independently account for some curvature in running paths. A more rigorous test requires directly examining the optical trajectories when fielders are pursuing uncatchable balls. Direct recordings of the optical trajectories allow comparison of when OAC alignment and LOT predictions break down, as they must for missed balls.

Experiment 2

In Experiment 2, we directly examine the optical trajectory of uncatchable balls and test if fielders maintain the control heuristic of linearity longer than speed constancy. When pursuing uncatchable balls, the fielder will reach a point at which he or she must sacrifice either optical linearity or lateral alignment at the expense of the other. He or she must either maintain alignment longer and allow the ball trajectory to curve or maintain linearity longer and compel the optical trajectory to laterally accelerate or decelerate to match the vertical component. Given this choice, presumably he or she will opt to maintain the dominant heuristic. If linearity is maintained significantly longer than speed constancy, this is evidence that the LOT strategy is the dominant lateral control heuristic. If linearity is not maintained longer, this is evidence that OAC alignment is the dominant lateral control heuristic. In short, Experiment 2 tests for the dominant lateral control heuristic by testing which strategy is maintained longer.

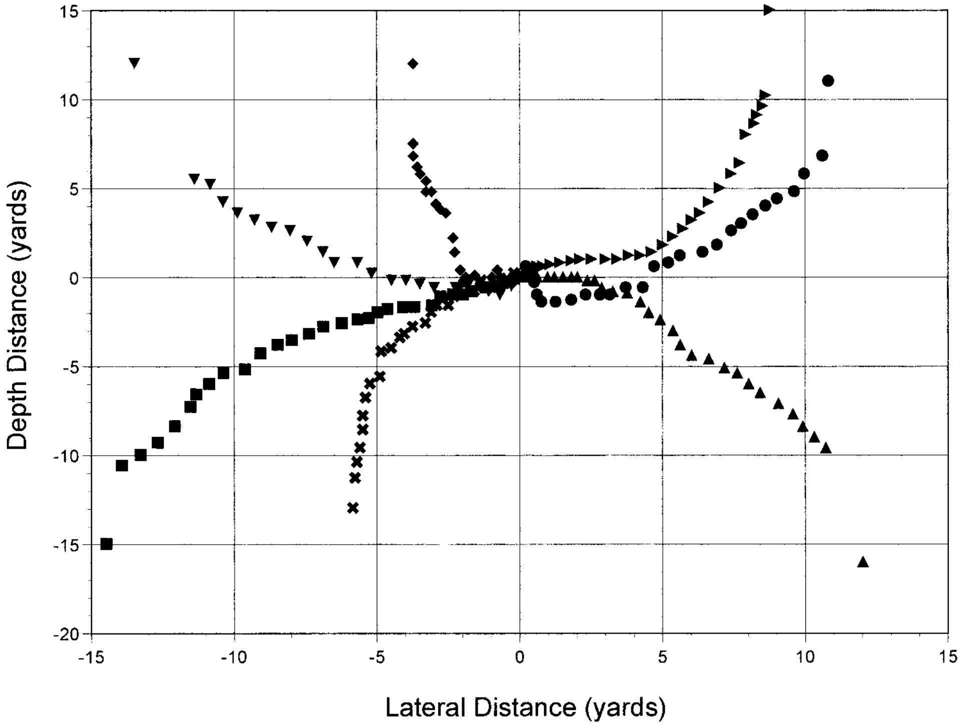

Figure 5. Sample empirical running paths for uncatchable balls headed in front and over the head of fielders: Frame-by-frame positions of sample empirical running paths of fielders chasing uncatchable fly balls headed in front and over their heads (frame rate = 10/s). For balls headed in front of fielders, the paths tend to curve to the side and forward toward the destination point. For balls headed behind fielders, the paths tend to curve to the side and backward toward the destination point. The actual landing location of the ball is shown using the same symbol as each running path, but removed from the last running-path coordinate by 2.5 to 7 yards (2.3 to 6.4 m). The average speed of fielders was between 4 and 5.5 yards/s (3.7 and 5 m/s), near their top speed of just under 5.5 yards/s (5 m/s).

Figure 6 (A and B) shows the predictions of the OAC alignment and LOT models, respectively, for uncatchable balls headed in front of fielders. Figure 7 (A and B) shows the predictions of the OAC alignment and LOT models, respectively, for uncatchable balls headed beyond fielders. For balls headed to land in front of the fielder, the vertical component will decelerate. The OAC alignment strategy specifies that fielders will maintain a near constant increase in the horizontal optical angle, β, while the vertical optical angle, α, decelerates. This results in an optical trajectory that slows down vertically and curves out to the side (see Figure 6A). The LOT strategy specifies that the rate of lateral optical change will match the decelerating vertical optical movement. This results in an optical trajectory that remains straight but slows down (see Figure 6B). For balls headed to land beyond the fielder, the vertical component will accelerate. Here the OAC alignment strategy results in an optical trajectory that speeds up vertically and curves upward (see Figure 7A). In contrast, the LOT strategy specifies an optical trajectory that remains straight but speeds up (see Figure 7B). The hypothesis supportive of OAC alignment is that optical speed constancy for the ball will be maintained longer than optical linearity. The hypothesis supportive of the LOT model is that optical linearity for the ball will be maintained longer than optical speed constancy. The hypothesis supportive of OAC alignment is that the optical linearity for the ball will not be maintained longer than optical speed constancy.

Method

Subjects. The same 5 skilled outfielders used in Experiment 1 fielded fly balls.

Apparatus. A shoulder-mounted video camera was used to record the optical trajectory of the ball as fielders pursued uncatchable fly balls. Before data were collected, all of the fielders had considerable practice looking through the viewfinder with one eye and aiming the camera toward the ball while trying to catch it. They attained a level of proficiency such that the camera task did not interfere with their natural ball-catching behavior.

Instructions given to fielders. The instructions given to fielders were the same as in Experiment 1. They were told to go all out to catch all of the fly balls. In addition, fielders were requested to verbally indicate if and when they became aware that they would not be able to catch the ball. Fielders were trained with pilot trials and debriefed several times, as they were in Experiment 1, to verify that they were going all out on every trial. Similarly, we again included occasional catchable balls so they did not know the outcome ahead of time, and we confirmed their continuous efforts with both self-reports and experimenter observations.

Design and procedure. The fielders stood about 50 m (170 ft) from where the ball was launched. The ball was launched at random distances between 10 and 70 m in depth either in front of, near, or behind the fielder's initial position and between 0 and 20 m to the fielder's right or left. A thrower visible to the fielder launched balls that were catchable mixed with ones that were uncatchable. Use of a visible thrower may provide additional cues for the fielder, but it is also similar to a typical

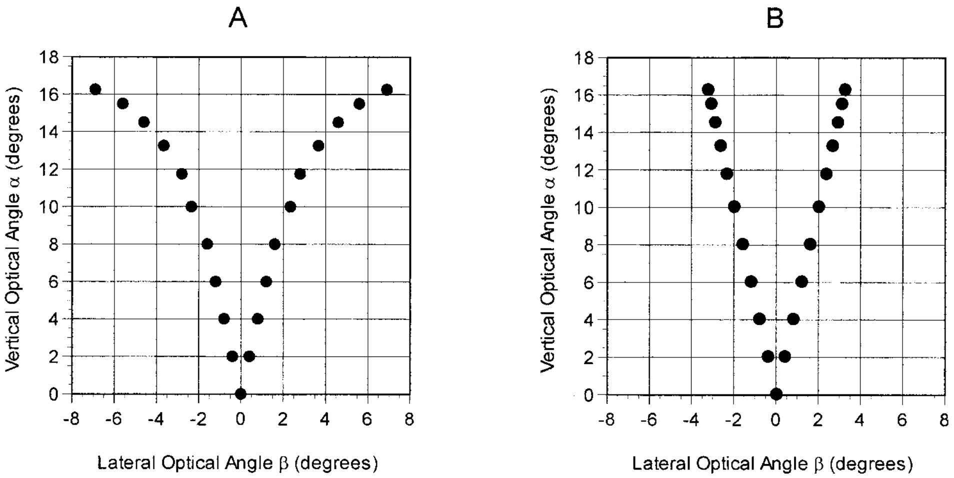

Figure 6. Optical predictions of the optical acceleration cancellation (OAC) alignment and linear optical trajectory (LOT) models for balls headed too far in front. A: The OAC alignment model predicts that fielders will maintain a near constant increase in the lateral optical angle, β, for uncatchable balls headed too far in front and to the side, whereas the vertical optical angle, α, will decelerate (causing the optical ball trajectory to curve outward). B: The LOT model predicts that both the lateral optical angle, β, and the vertical optical angle, α, will decelerate at a matched rate as fielders continue to maintain a straight optical ball trajectory in lieu of optical speed constancy.

real-world ball-catching setting (Morgan & McBeath, 2001). The order in which variations of catchable and uncatchable balls were thrown was randomized to limit anticipation by the fielder for any one type of fly ball. The thrower was positioned at a designated spot in front of a marked wall inside of an indoor field house. This was done so that the video sequence of optical ball movement could be coded relative to the background wall and ceiling throughout its trajectory.

The optical trajectory was measured by recording the ball position for each video frame onto a transparency taped to the video monitor. The transparency was moved frame-by-frame on a video monitor to keep the background aligned. Visual angle was calibrated by converting the pixel height of the thrower on the video image to the actual visual angle of the thrower that was observed at the time of recording. The initial location of the ball out of the thrower's hand was marked as the starting point, or (0, 0) coordinate. The data were coded as pixel movement and then converted to degrees visual angle. This conversion produces very precise visual angles provided the ball is compared with background scenery that is distant and remains within a small visual angle of it. In this work, the comparison background scenery was always within 1° visual angle of the ball, well within the region of the law of small angles. We also had static

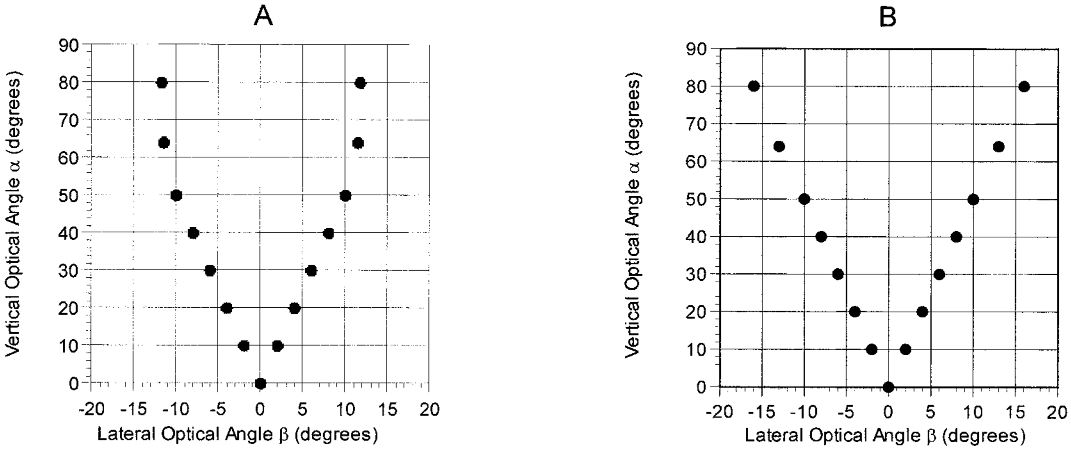

Figure 7. Optical predictions of the optical acceleration cancellation (OAC) alignment and linear optical trajectory (LOT) model for balls headed too far overhead. A: The OAC alignment model predicts that fielders will maintain a near constant increase in the lateral optical angle, β, for uncatchable balls headed too far over their heads, whereas the vertical optical angle, α, will accelerate (causing the optical ball trajectory to curve upward). B: The LOT model predicts that both the lateral optical angle, β, and the vertical optical angle, α, will accelerate at a matched rate as fielders continue to maintain a straight optical ball trajectory in lieu of optical speed constancy.

test trials in which we varied the angle of the camera and verified that any errors in the optical angle were insignificant. Thirty-six trials were coded in which both the fielder tried but did not quite catch the ball and the ball remained within the field of view of the camera throughout most or the entire time the ball was in the air.

Results

We analyzed how long the ball image was maintained along a straight optical line (as predicted by the LOT model) versus how long the ball image was maintained at a constant optical speed (as predicted by the OAC alignment model) for the 36 trials. Specifically, we determined the portion of the trajectory for which spatial linearity was maintained to a degree that accounted for at least 95% of the variance in optical ball movement and the portion of the trajectory for which optical ball speed was maintained so that it did not significantly increase or decrease (again using a 95% confidence criterion). We then analyzed (a) the percentage of trials in which optical spatial linearity of the ball broke down significantly later than optical speed constancy and (b) the average time differential (in 0.03-s frames) that optical spatial linearity broke down after optical temporal constancy.

Balls headed too far in front. In 20 trials, the ball was both uncatchable and landed in front of the fielder. In 17, or 85%, of these trials a LOT was maintained significantly longer than OAC. This provided significant support, as measured by a sign test, $z(20) = 4.90$, $p < .001$. Thus, spatial linearity reliably broke down later than temporal constancy, as predicted by the LOT model. For the 20 trials with balls landing in front of the fielder, the spatial LOT strategy broke down an average of almost a full second (25 0.03-s frames) later than did the temporal OAC strategy. Figure 8A shows sample empirical patterns of optical trajectories of balls that landed in front of fielders. The lines over each of the trajectories shown in the figure are estimates of the best-fit lines used to compute the R^2 values. They help illustrate the extent to which the trajectories remained close to straight lines while the optical speed notably slowed down.

Balls headed too far overhead. In 16 trials, the ball landed beyond the fielder. In all 16 of these trials, a LOT was maintained significantly longer than OAC. This finding provided significant support for the LOT model, as revealed by a sign test, $z(16) = 5.65$, $p < .001$. Thus, spatial linearity reliably broke down later than temporal constancy in every case of balls headed beyond the fielder, as predicted by the LOT model. For these 16 trials, the spatial LOT strategy broke down, on average, over two-thirds of a second (22 0.03-s frames) later than the temporal OAC strategy. Figure 8B shows sample empirical patterns of optical trajectories of balls that landed beyond fielders. The lines over each of the trajectories shown in the figure are estimates of best-fit lines used to compute R^2 values. As was the case for balls that landed in front of the fielder, the trajectories remained close to straight lines, but here the optical speed notably accelerated.

Figure 8 (A and B) shows that some of the trajectories had some curve to them near the end of the trials. The optical path was expected to deviate from linearity because these were balls that

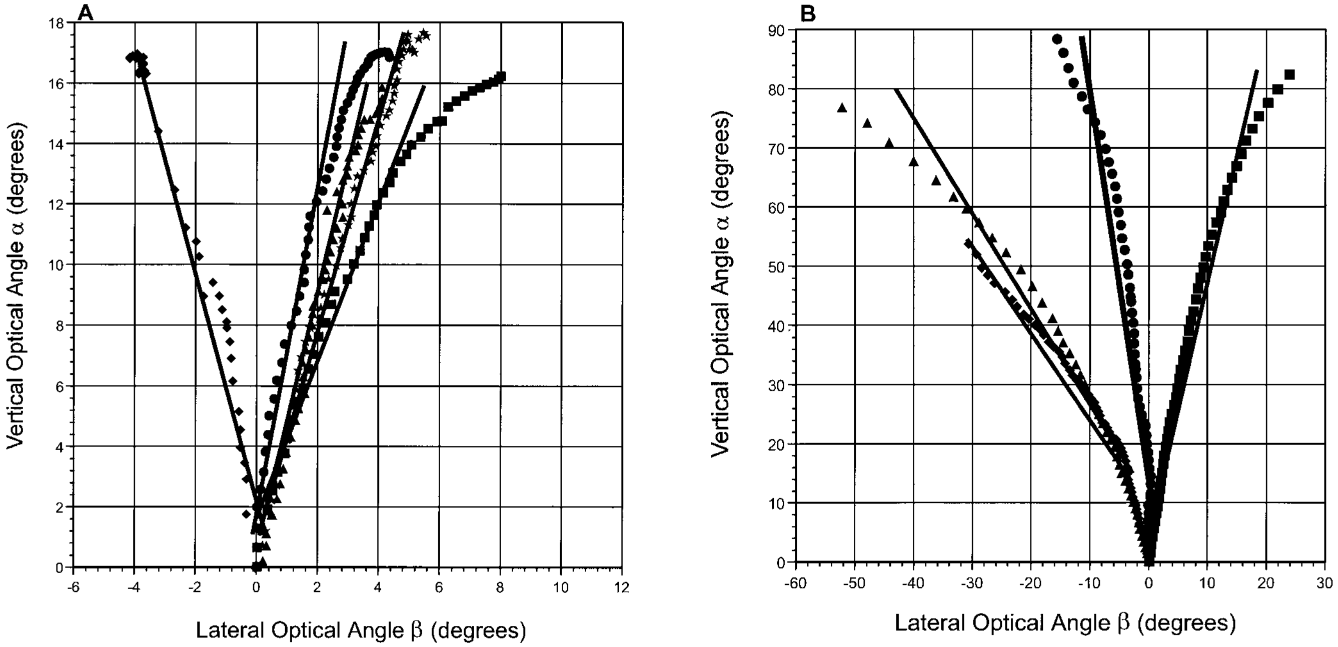

Figure 8. Empirical optical trajectories for uncatchable fly balls: Initial portions of empirical optical trajectories during which a linear optical trajectory (LOT) is maintained to a degree that accounts for 95% of the variance and limited to a vertical optical angle of 90°. Successive ball positions are depicted sequentially, rising in 0.03-s increments. A: The ball is headed too far in front of the fielder; the optical ball speed notably decelerates both vertically and laterally, indicating that the fielder is abandoning alignment to favor a LOT. B: The ball is headed too far over the head of the fielder; the optical ball speed notably accelerates both vertically and laterally, again indicating that the fielder is abandoning alignment to favor a LOT.

were not caught (i.e., even though spatial linearity broke down significantly later than temporal constancy, it eventually broke down while the ball was still in the air). However, the portion of the trajectories that is shown still maintained linearity to the 95% criterion from the perspective of the video camera.

On three trials, fielders verbally indicated when they were sure they could no longer catch the ball. They made this specification 19, 20, and 22 frames after the LOT no longer accounted for 95% of the variance in optical ball movement. On one trial, the fielder stated that he would catch a ball that he did not quite reach, narrowly missing it by only a fraction of a meter. He made his statement within 1 frame of when the LOT no longer accounted for 95% variance in optical ball movement. Although the self-report data were sparse, it remained consistent with the idea that maintaining a LOT to this degree of precision gave the fielder the impression that he or she would succeed in making a catch once optical ball size began to notably increase.

General Discussion

Our findings support the hypothesis that for uncatchable balls, the LOT strategy is maintained for a notably longer period of time than is the OAC strategy. In Experiment 1, fielders maintained running paths that curved in the direction that was consistent with the LOT strategy significantly more often than straighter paths that were better laterally aligned and consistent with an OAC alignment strategy. In the vast majority of cases, fielders did not strive to maintain alignment but rather chose running paths that curved toward the ball.

In the direct test of optical behavior used in Experiment 2, the fielders reliably maintained the straight optical path predicted by the LOT strategy notably longer than they did temporal constancy, in contrast to the prediction of OAC alignment. Spatial linearity was maintained over 0.67 s longer than was temporal constancy for balls landing both too far in front and too far beyond the fielders. Temporal constancy broke down in a manner consistent with the maintenance of the LOT model in 92% of all cases (both balls headed in front and overhead). For balls landing in front of fielders, the optical ball speed decelerated, whereas for those landing beyond, it accelerated. Thus, when fielders are in a situation in which they are forced to choose between maintaining optical linearity of the ball and alignment, they elect the former. The findings confirm the dominance of the LOT heuristic over OAC alignment for uncatchable balls headed off to the side.

One intriguing aspect of the optical path for missed balls that can be seen in Figure 8B is that the breakdown in optical linearity is typically due to curvature in the outward direction and appears to be most notable starting at a vertical elevation angle of about 70°. Although such curvature may seem inconsistent with ideal obeisance of the LOT heuristic, it is even more inconsistent with ideal obeisance of alignment (which would produce optical curvature in the opposite, upward direction). Fielders apparently select running paths that head backward somewhat more than the LOT ideal and much more than the alignment ideal. Given that optical linearity must break down eventually for uncatchable balls, it is not particularly notable that this occurs. The elevation angle of 70° where noticeable deviation begins is also not arbitrary. This is the approximate angle at which slant angles are estimated to be relatively indistinguishable from vertical walls. (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Perhaps fielder notions of vertical and lateral optical angles become more ambiguous when α exceeds 70°. Certainly we would expect some kind of spatial angle reorientation when α reaches 90° and the ball crosses over the fielder's head, as in the case of one of the trials shown in Figure 8B.

In our work, we intentionally described the relationship between fielder and ball only in terms of optical angles, without addressing the intricacies of the sensorimotor integration of retinal and gaze signals involved in pursuing and catching a fly ball. Recent work by Oudejans et al. (1999) has found that fielders generally keep their eyes fixated on the moving ball. Other work of ours with robots has also found that keeping the eye fixated on the moving ball leads to a more robust control algorithm than keeping it stationary relative to the background and monitoring ball movement (see also Priebe, Churchland, & Lisberger, 2001). Considerable research has examined the retinal and extraretinal mechanisms required to accurately initiate and maintain tracking of moving targets (Bahill & LaRitz, 1984; Barnes & Asselman, 1991; Becker & Fuchs, 1985; Crane & Demer, 1997; Dallos & Jones, 1963; Kao & Morrow, 1994; Kowler, van der Steen, Tamminga, & Collewijn, 1984; Lisberger, Evinger, Johanson, & Fuchs, 1981; Rashbass, 1961; Robinson, 1965; Shaffer, Krisky, Kmiec, Luna, & Sweeney, 1998; Tychsen & Lisberger, 1986; Yasui & Young, 1984). Although it is clear that these mechanisms play a significant role in tracking moving targets, the optical information is still clearly available from the perspective of the fielder to be used to guide motion of the eyes and the head and ascertain the ongoing optical angle.

Virtually all previous studies investigating the mechanisms by which outfielders navigate to and intercept fly balls are limited to only examining successful attempts. In the present work, we explored situations in which fielders fail. We suggest that to fully understand how a system works, it is often necessary to examine cases of failure. Competing models of fielding strategies may all converge and be difficult to discriminate when examining only successful interception of the ball before it reaches the ground. When fielders successfully intercept balls headed to the side, both a LOT and OAC are typically maintained. Only when uncatchable trials are examined and both strategies must break down do notable differences emerge in the behavior predicted by the control parameters. The uncatchable-ball situation allows measurement of the extent to which fielders elect to maintain optical linearity and speed constancy independent of each other. Typically, fielders do not initially know where a ball is headed to land (McLeod & Dienes, 1993). Further evidence of this comes from the frequency with which baseball fielders chase balls until a fence or the backstop impedes them, even for ones headed well beyond the impediment. The present study supports that fielders do not need to know whether a ball is catchable in deciding their lateral strategy. Maintenance of a monotonically rising LOT will help guide them to the interception point when the ball is catchable and will lead them on a curved running path directed toward the landing point when it is not.

We note that in some cases, the absolute value of the optical projection angle that a ball is traveling along, Ψ, might almost immediately indicate that the ball is uncatchable. When Ψ is anywhere near the horizon, the ball is always uncatchable, so the fielder could immediately abandon the LOT and OAC strategies for an alternative one. If a ball with this extreme a projection angle has a high enough velocity to reach the fielder in the depth direction, it will also have enough lateral velocity to send it too far to the side to be catchable. We did not test cases that are this extreme, but the possibility of an additional cue could explain fielder behavior in extreme cases. In such cases, once a fielder realizes that the ball is uncatchable, he or she may no longer concentrate on navigating toward the point of impact and would likely head in the direction to be in the best position to be of assistance in the play. Thus, the optical projection angle, Ψ, may provide an immediate spatial cue about whether the ball is catchable or uncatchable that experienced fielders could learn to use.

The LOT strategy allows fielders to both pursue and catch target projectiles. The present study suggests that the breakdown of optical linearity may provide a criterion indicating when targets are uncatchable and when alternative strategies of pursuit might be initiated. The present work supports the view that the LOT strategy is the principal tracking strategy used when balls are headed to the side near a fielder. We found that fielders initially maintain a constant relative angle of motion for uncatchable balls like they do for catchable ones. The findings suggest that maintenance of this strategy will ensure collision with the ball if it is catchable and direct the fielder toward the landing point when it is not.

The use of the LOT strategy as a principal cue for tracking both catchable and uncatchable fly balls may be related to more general navigational heuristics used by humans (Bruce & Green, 1990; Campiani, Giachetti, & Torre, 1995; Cutting, Springer, Braren, & Johnson, 1992; Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999; van den Berg, 1993; Vishton & Cutting, 1995; Wickens, 1992). For instance, airplane pilots are very accurate at spatial-error-nulling tasks and perform particularly well in pursuit-tracking tasks that allow them to anticipate and maintain constant angle position relative to a target (Adams, 1961; Beall & Loomis, 1997; Roscoe, 1968).

Predators and organisms tracking mates also appear to exhibit behaviors in which they adjust their position to maintain control of relative angle of motion between the pair. The findings of tracking research with houseflies (*Fannia canicularis*) and teleost fish (*Acanthaluteres spilomelanurus*) indicate that they *lock on* to the motion of their target in a way that maintains optical angle constancy (Collett & Land, 1975; Lanchester & Mark, 1975; Land & Collett, 1974). Land and Collett (1974) found that houseflies in pursuit of mates maintained an angle of pursuit that was a function of their path curvature. Maintenance of optical angle constancy to guide pursuit also has been found in tethered flies and free-flying houseflies (*Musca domestica L.*) (Reichardt & Poggio, 1979; Wagner, 1986; Wehrhahn, Poggio, & Buelthoff, 1982). Zhang, Xiang, Zili, and Srinivasan (1990) found that bees, like flies, control their angular orientation and velocity to track a moving target as they approach it. Similarly, flush-pursuer birds such as the painted redstart (*Myioborus pictus*) use tail-fanning and plumage contrast to decrease the angular speed of the prey's image on the bird's retina to guide their pursuit of their prey's escape trajectory (Jablonski, 1998).

Research on the tracking characteristics of bats are consistent with their using echolocation during the pursuit stage of their flight to initially maintain optical angle constancy between themselves and their prey (Kuc, 1994; Masters, Moffat, & Simmons, 1985; Simmons, Fenton, & O'Farrell, 1979; Simmons & Kick, 1983; Webster & Griffin, 1962). The pursuit paths used by bats chasing prey appear to be related to and consistent with those of air-to-air missile guidance systems (Kuc, 1994). Our research suggests that fielders also use a related strategy to attempt to maintain control over their position relative to the ball for as long as possible while pursuing it. The commonality of all of these examples appears to be the use of a simple geometric optical strategy to guide pursuit.

The optical strategies used by baseball fielders represent intriguing examples of control theory principles based solely on invariant properties that are perceptually discernible from the perspective of the moving fielder. In the past decade, two such strategies have been demonstrated when pursuing and intercepting a moving target such as a fly ball: first, the temporal strategy of maintenance of optical speed constancy, and second, the spatial strategy of maintenance of a monotonically increasing LOT. The convergence of evidence from this and previous research has shown that both are used to intercept targets headed off to the side but that the spatial LOT strategy is dominant.

References

Aboufadel, E. (1996). A mathematician catches a baseball. *American Mathematical Monthly, 103,* 870–878.

Adams, J. A. (1961). Human tracking behavior. *Psychological Bulletin, 58,* 55–79.

Alderson, G. J. K., Sully, D. J., & Sully, H. G. (1974). An operational analysis of a one-handed catching task using high speed photography. *Journal of Motor Behavior, 6,* 217–226.

Babler, T. G., & Dannemiller, J. L. (1993). Role of image acceleration in judging landing location of free-falling projectiles. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 15–31.

Bahill, A. T., & LaRitz, T. (1984). Why can't batters keep their eyes on the ball? *American Scientist, 72,* 249–253.

Barnes, G. R., & Asselman, P. T. (1991). The mechanism of prediction in human smooth pursuit eye movements. *Journal of Physiology, 439,* 439–461.

Beall, A. C., & Loomis, J. M. (1997). Optic flow and visual analysis of the base-to-final turn. *International Journal of Aviation Psychology, 7,* 201–223.

Becker, W., & Fuchs, A. F. (1985). Prediction in the oculomotor system: Smooth pursuit during transient disappearance of a visual target. *Experimental Brain Research, 57,* 562–575.

Bruce, V., & Green, P. R. (1990). *Visual perception: Physiology, psychology, and ecology* (pp. 241–285). Hillsdale, NJ: Erlbaum.

Calderone, J. B., & Kaiser, M. K. (1989). Visual acceleration detection: Effect of sign and motion orientation. *Perception & Psychophysics, 45,* 391–394.

Campiani, M., Giachetti, A., & Torre, V. (1995). Optic flow and autonomous navigation. *Perception, 24,* 253–267.

Chapman, S. (1968). Catching a baseball. *American Journal of Physics, 36,* 868–870.

Collett, T. S., & Land, M. F. (1975). Visual control of flight behavior in the hoverfly *Syritta pipiens L. Journal of Comparative Physiology,* 99, 1–66.

Cornilleau-Peres, V., & Droulez, J. (1989). Visual perception of surface curvature: Psychophysics of curvature detection induced by motion parallax. *Perception & Psychophysics, 46,* 351–364.

Cornilleau-Peres, V., & Droulez, J. (1992). Spatial constancy and the visual perception of surface curvature from optical flow. *Irish Journal of Psychology, 13,* 508–523.

Crane, B. T., & Demer, J. L. (1997). Human gaze stabilization during natural activities: Translation, rotation, magnification, and target distance effects. *Journal of Neurophysiology, 78,* 2129–2144.

Cutting, J. E., Springer, K., Braren, P. A., & Johnson, S. H. (1992). Wayfinding on foot from information in retinal, not optical flow. *Journal of Experimental Psychology: General, 121,* 41–72.

Dallos, P. J., & Jones, R. W. (1963). Learning behavior of the eye fixation control system. *IEEE Transactions on Automatic Control, 8,* 218–227.

Dannemiller, J. L., Babler, T. G., & Babler, B. L. (1996, July 12). On catching fly balls. *Science, 273,* 256–257.

Dienes, Z., & McLeod, P. (1993). How to catch a cricket ball. *Perception, 22,* 1427–1439.

Foster, D. H., Simmons, D. R., & Cook, M. J. (1993). The cue for contour–curvature discrimination. *Vision Research, 33,* 329–341.

Gottsdanker, R. M. (1956). The ability of human operators to detect acceleration of target motion. *Psychological Bulletin, 53,* 477–487.

Gottsdanker, R. M., Frick, J. W., & Lockard, R. B. (1961). Identifying the acceleration of visual targets. *British Journal of Psychology, 52,* 31–42.

Hopkins, J. R., Kagan, J., Brachfeld, S., Hans, S., & Linn, S. (1976). Infant responsivity to curvature. *Child Development, 17,* 1166–1171.

Jablonski, P. (1998). A rare predator exploits prey escape behavior: The role of tail-fanning and plumage contrast in foraging of the painted redstart (*Myioborus pictus*). *Behavioral Ecology, 10,* 7–14.

Jacobs, T. M., Lawrence, M. D., Hong, K., Giordano, N., & Giordano, N. (1996, July 12). On catching fly balls. *Science, 273,* 257–258.

Jagacinski, R. J., Burke, M. W., & Miller, D. P. (1977). Use of schemata and acceleration information in stopping a pendulumlike system. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 212–223.

Kaiser, M. K., & Mowafy, L. (1993). Optical specification of time-to-passage: Observers' sensitivity to global tau. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1028–1040.

Kao, G. W., & Morrow, M. J. (1994). The relationship of anticipatory smooth eye movement to smooth pursuit initiation. *Vision Research, 22,* 3027–3036.

Kowler, E., van der Steen, J., Tamminga, E. P., & Collewijn, H. (1984). Voluntary selection of the target for smooth pursuit eye movement in the presence of superimposed, full-field stationary and moving stimuli. *Vision Research, 24,* 1789–1798.

Kramer, D., & Fahle, M. (1996). A simple mechanism for detecting low curvature. *Vision Research, 36,* 1411–1419.

Kuc, R. (1994). Sensorimotor model of bat echolocation and prey capture. *Journal of the Acoustical Society of America, 96,* 1965–1978.

Lanchester, B. S., & Mark, R. F. (1975). Pursuit and prediction in the tracking of moving food by a teleost fish (*Acanthaluteres spilomelanurus*). *Journal of Experimental Biology, 63,* 627–645.

Land, M. F., & Collett, T. S. (1974). Chasing behavior of houseflies (*Fannia canicularis*). *Journal of Comparative Physiology, 89,* 331–357.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5,* 437–459.

Lenoir, M., Musch, E., Janssens, M., Thiery, E., & Uyttenhove, J. (1999). Intercepting moving objects during self-motion. *Journal of Motor Behavior, 31,* 55–67.

Lisberger, S. G., Evinger, C., Johanson, G. W., & Fuchs, A. F. (1981). Relationship between eye acceleration and retinal image velocity during foveal smooth pursuit in man and monkey. *Journal of Neurophysiology, 46,* 229–249.

Marken, R. S. (1997). The dancer and the dance: Methods in the study of living control systems. *Psychological Methods, 2,* 436–446.

Masters, W. M., Moffat, A. J. M., & Simmons, J. A. (1985, June 14). Sonar tracking of horizontally moving targets by the big brown bat, *Eptesicus fuscus. Science, 228,* 1331–1333.

McBeath, M. K. (1990). The rising fastball: Baseball's impossible pitch. *Perception, 19,* 545–552.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1995a, April 28). How outfielders determine where to run to catch fly balls. *Science, 268,* 569–573.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1995b, June 23). Play ball! *Science, 268,* 1683–1685.

McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1996, July 12). On catching fly balls. *Science, 273,* 258–260.

McLeod, P., & Dienes, Z. (1993, March 4). Running to catch the ball. *Nature, 362,* 23.

McLeod, P., & Dienes, Z. (1996). Do fielders know where to go to catch the ball or only how to get there? *Journal of Experimental Psychology: Human Perception and Performance, 22,* 531–543.

Michaels, C. F., & Oudejans, R. D. (1992). The optics and actions of catching fly balls. *Ecological Psychology,* 4, 199–222.

Montagne, G., Laurent, M., & Durey, A. (1998). Visual guidance of goal-oriented locomotor displacements: The example of ball interception tasks. *Ecological Psychology, 10,* 25–37.

Morgan, S. E., & McBeath, M. K. (2001). *Group center of attention as a guide to a baseball's destination.* Manuscript submitted for publication.

Norman, J. F., & Lappin, J. S. (1992). The detection of surface curvatures defined by optical motion. *Perception & Psychophysics, 51,* 386–396.

Ogilvie, J., & Daicar, E. (1967). The perception of curvature. *Canadian Journal of Psychology/Review of Canadian Psychology, 21,* 521–525.

Oudejans, R. R. D., Michaels, C. F., Bakker, F. C., & Davids, K. (1999). Shedding some light on catching in the dark: Perceptual mechanisms for catching fly balls. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 531–542.

Peper, L., Bootsma, R. J., Mestre, D. R., & Bakker, F. C. (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 591–612.

Priebe, N. J., Churchland, M. M., & Lisberger, S. G. (2001). Reconstruction of target speed for the guidance of pursuit eye movements. *Journal of Neuroscience, 21,* 3196–3206.

Proffitt, D. R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin & Review, 2,* 409–428.

Rashbass, C. (1961). The relationship between saccadic and smooth tracking eye movements. *Journal of Physiology, 159,* 326–338.

Regan, D. M., Kaufman, L., & Lincoln, J. (1986). Motion in depth and visual acceleration. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Sensory processes and perception* (Vol. 1, pp. 19.1–19.146). New York: Wiley.

Reichardt, W., & Poggio, T. (1979). Figure–ground discrimination by relative movement in the visual system of the fly. *Biological Cybernetics, 35,* 81–100.

Riggs, L. A. (1973, September 14). Curvature as a feature of pattern vision. *Science, 181,* 1070–1072.

Robinson, D. A. (1965). The mechanics of human smooth pursuit eye movement. *Journal of Physiology, 180,* 569–591.

Roscoe, S. N. (1968). Airborne displays for flight and navigation. *Human Factors, 10,* 321–332.

Runeson, S. (1974). Constant velocity—Not perceived as such. *Psychological Research, 37,* 3–23.

Runeson, S. (1975). Visual prediction of collision with natural and nonnatural motion functions. *Perception & Psychophysics, 18,* 261–266.

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.

Savelsbergh, G. J. P., Whiting, H. T. A., & Bootsma, R. J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 315–322.

Schmerler, J. (1976). The visual perception of accelerated motion. *Perception, 5,* 167–185.

Shaffer, D. M., Krisky, C. M., Kmiec, J. A., Luna, B., & Sweeney, J. A. (1998, November). *Dramatic effect of prediction on smooth pursuit eye movements.* Paper presented at the meeting of the Society for Neuroscience, Los Angeles.

Shaffer, D. M., & McBeath, M. K. (1997). [Responses concerning catching fly balls hit off to the side and directly toward an outfielder]. Unpublished raw data.

Simmons, J. A., Fenton, M. B., & O'Farrell, M. J. (1979, January 5). Echolocation and pursuit of prey by bats. *Science, 203,* 16–21.

Simmons, J. A., & Kick, S. A. (1983). Interception of flying insects by bats. In F. Huber & H. Mark (Eds.), *Behavioral physiology and neuroethology: Roots and growing points.* New York: Springer.

Timney, B. N., & MacDonald, C. (1978). Are curves detected by "curvature detectors"? *Perception, 7,* 51–64.

Todd, J. T. (1981). Visual information about moving objects. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 8795–8810.

Tresilian, J. R. (1990). Perceptual information for the timing of interceptive action. *Perception, 19,* 223–239.

Tresilian, J. R. (1995). Study of a servo-control strategy for projectile interception. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 48*(A), 688–715.

Tychsen, L., & Lisberger, S. G. (1986). Visual motion processing for the initiation of smooth-pursuit eye movements in humans. *Journal of Neurophysiology, 56,* 953–968.

van den Berg, A. V. (1993, October 7). Perception of heading. *Nature, 365,* 497–498.

Vishton, P. M., & Cutting, J. E. (1995). Wayfinding, displacements, and mental maps: Velocity fields are not typically used to determine one's aimpoint. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 978–995.

Wagner, H. (1986). Flight control and visual control of flight in the free-flying housefly (*Musca domestica L.*). *Philosophical Transactions of the Royal Society of London, Series B, 312,* 527–595.

Watt, R. J., & Andrews, D. P. (1982). Contour curvature analysis: Hyperacuities in the discrimination of detailed shape. *Vision Research, 22,* 449–460.

Webster, F. A., & Griffin, D. R. (1962). The role of flight membranes in insect capture by bats. *Animal Behavior, 3–4,* 332–340.

Wehrhahn, C., Poggio, T., & Buelthoff, H. (1982). Tracking and chasing in houseflies (*Musca*): An analysis of 3-d flight trajectories. *Biological Cybernetics, 45,* 123–130.

Weiss, P., & Jeannerod, M. (1998). Getting a grasp on coordination. *News in Physiological Sciences, 13,* 70–75.

Werkhoven, P., Snippe, H. P., & Toet, A. (1992). Visual processing of optic acceleration. *Vision Research, 32,* 2313–2329.

Wickens, C. D. (1992). Process control and automation. In *Engineering psychology and human performance* (2nd ed., pp. 466–481). New York: HarperCollins.

Yasui, S., & Young, L. R. (1984). On the predictive control of foveal eye tracking and slow phases of optokinetic and vestibular nystagmus. *Journal of Physiology, 347,* 17–33.

Zhang, S. W., Xiang, W., Zili, L., & Srinivasan, M. V. (1990). Visual tracking of moving targets by freely flying honeybees. *Visual Neuroscience, 4,* 379–386.

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