Journal of Experimental Psychology:
Human Perception and Performance
2003, Vol. 29, No. 6, 1244–1250

0096-1523/03/$12.00 DOI: 10.1037/0096-1523.29.6.1244

OBSERVATIONS

A Linear Optical Trajectory Informs the Fielder Where to Run to the Side to Catch Fly Balls

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P. McLeod, N. Reed, and Z. Dienes (2002) argued that the linear optical trajectory (LOT) strategy incorrectly cues fielders to run forward for balls headed beyond them. The authors of this article explain that the downward optical curvature found for balls landing beyond the fielder's initial position occurs because the balls reorient the direction the fielder is facing during pursuit. Thus, when downward optical curvature begins, the ball is headed to land in front of where the fielder is facing and running. This investigation of open-loop failure conditions has led to new insights such as the reorientation of the fielder, and it supports the use of maintaining matching rates of vertical and lateral optical ball movement consistent with primacy of the LOT control mechanism even when interception is unachievable.

In a recent article, McLeod, Reed, and Dienes (2002) highlighted an interesting feature of the optical trajectories of balls being pursued by fielders, as presented by Shaffer and McBeath (2002). They noted that there is downward optical curvature of the trajectories for balls headed beyond fielders. They suggested that this conflicts with the maintenance of linearity predicted by linear optical trajectory (LOT) theory and concluded that the LOT strategy must not be used for balls headed off to the side and beyond fielders. In this article, we explain this seeming anomaly.

LOT and Optical Acceleration Cancellation (OAC) Alignment Strategies and Tracking Uncatchable Balls

The geometry of the optical image defined by using a LOT for a caught ball is shown in Figure 1. A LOT results when the fielder's running speed and direction maintain a rate of increase in the lateral optical angle, β, that matches the rate of increase in the vertical optical angle, α (McBeath, Shaffer, & Kaiser, 1995a; Shaffer & McBeath, 2002). We mathematically define α and β as the sum of all instantaneous changes in vertical and lateral optical ball position. We also note that when fielders run off to the side to catch fly balls, they simultaneously maintain a constant increase in the tangent of the vertical optical angle, $\tan\alpha$, which serves as a complementary cue in addition to optical linearity (McBeath, Shaffer, & Kaiser, 1995b; Shaffer & McBeath, 2002). This cue is referred to as OAC and is shown in Figure 2. Thus, we view a LOT and OAC as complementary optical strategies that are used together when fielders are pursuing balls headed to the side.

The contrasting model for lateral guidance prior to the introduction of the LOT is for fielders to simply maintain lateral alignment while performing OAC (Chapman, 1968). With research examining only caught balls, it is difficult to distinguish use of LOT versus OAC with alignment because the "closed loop" endpoint constrains the running path solutions to be very similar. Examination of the pursuit of "open loop" uncatchable balls provided a nice test to compare these two alternatives.

Shaffer and McBeath (2002) found that when fielders pursue fly balls headed off to the side, but beyond their reach, a LOT is maintained significantly longer and during significantly more trials than is OAC with alignment with the ball. That study compared the robustness of LOT and OAC alignment strategies and tested the conditions and manner in which they were forced to eventually break down (i.e., for degenerative cases of missed balls). We are encouraged that McLeod et al. (2002) also recognized that examining cases of failure is an important way to tease apart distinctions among models that may converge at the same solution in the case in which balls are successfully caught.

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We thank Wing Chan for data collection and coding.

Dennis M. Shaffer was a referee for "The Optic Trajectory Is Not a Lot of Use if You Want to Catch the Ball," by P. McLeod, N. Reed, and Z. Dienes, 2002, *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1499–1501.

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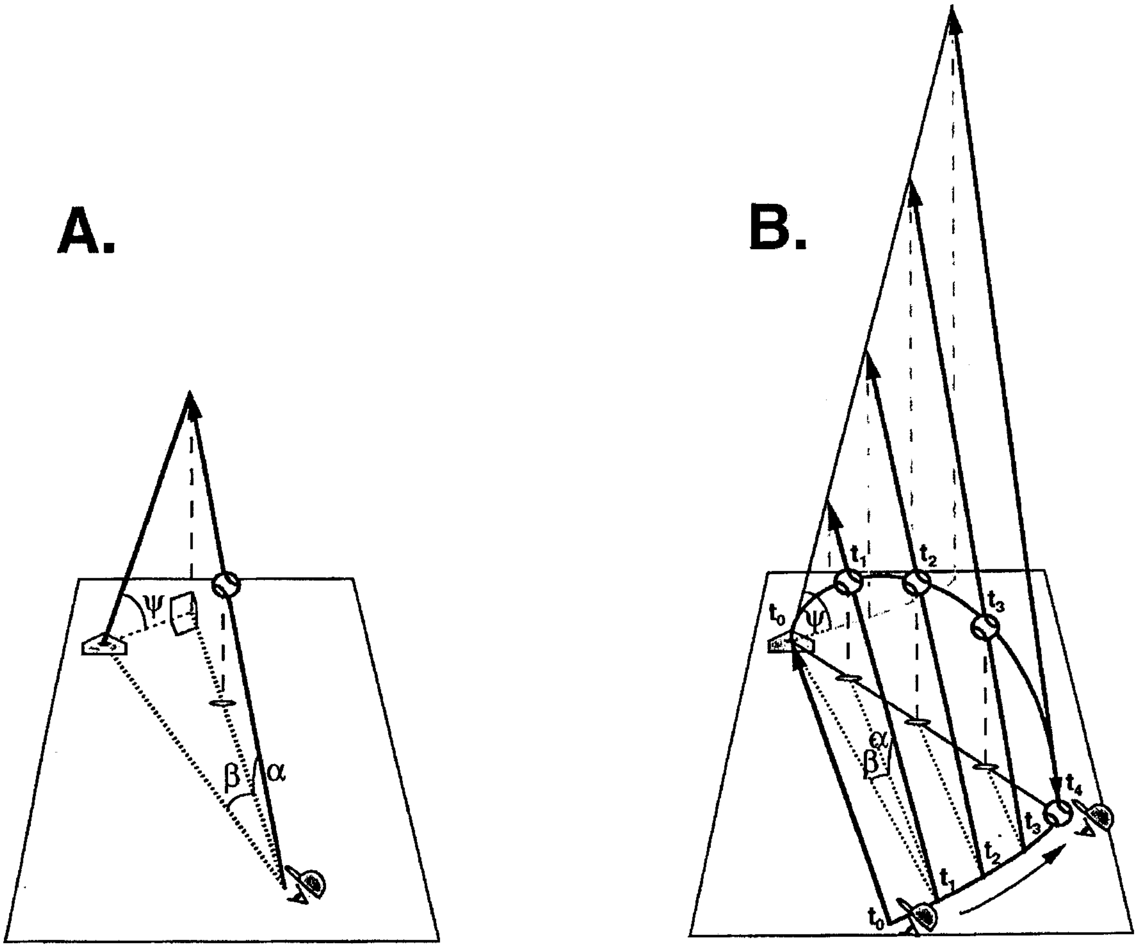

Figure 1. The linear optical trajectory (LOT) model. Shown is a center field bleacher view of a fielder converging on a ball headed to his or her right. The trapezoidal box represents the perspective projection of the ground plane. The optical trajectory is shown with vectors from the fielder's position through the ball. The LOT theory specifies that outfielders catch fly balls by running along a path that maintains a monotonically increasing linear optical ball trajectory. If the optical trajectory curves in any direction, the fielder adjusts his or her running path to null the curvature and keeps the image of the ball rising until they collide. This requires no knowledge of distance to or alignment with the ball. A: Optical angle definitions are α = vertical optical angle, β = lateral optical angle, and ψ = picture plane optical angle, where $\tan(\alpha)/\tan(\beta) = \tan(\psi)$, for a planar projection. Mathematically, α is defined as the sum of all instantaneous changes in vertical optical ball position, and β is defined as the sum of all instantaneous changes in lateral optical ball position. B: The LOT strategy 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. The resultant running path curves slightly and circles under the ball. t = time.

Curvature in the Optical Trajectories Is Expected for Balls That Are Not Going To Be Caught (i.e., for Degenerative Cases)

McLeod et al. (2002) pointed out that the optical trajectories shown in Figure 3 in the current article exhibited outward and downward optical curvature in trajectories where balls land beyond the fielder's starting position. We concur that there is curvature, particularly toward the ends of the trajectories shown in Figure 3. Shaffer and McBeath (2002) acknowledged previously that given that optical linearity must break down eventually for uncatchable balls, it is not particularly notable that this occurs. They also noted that when the optical trajectories departed from linearity, they typically curved in the outward direction (Shaffer & McBeath, 2002). They pointed out that although such curvature may seem inconsistent with ideal obeisance of the LOT strategy, it is even more inconsistent with ideal obeisance of OAC alignment (which would produce optical curvature in the opposite, upward direction).

In Shaffer and McBeath (2002), each of the partial optical trajectories was held to a criterion of a straight line (or LOT) accounting for at least 95% of the variance in optical ball movement throughout each of the optical trajectories analyzed, including those shown in Figure 3. This criterion was chosen to show the

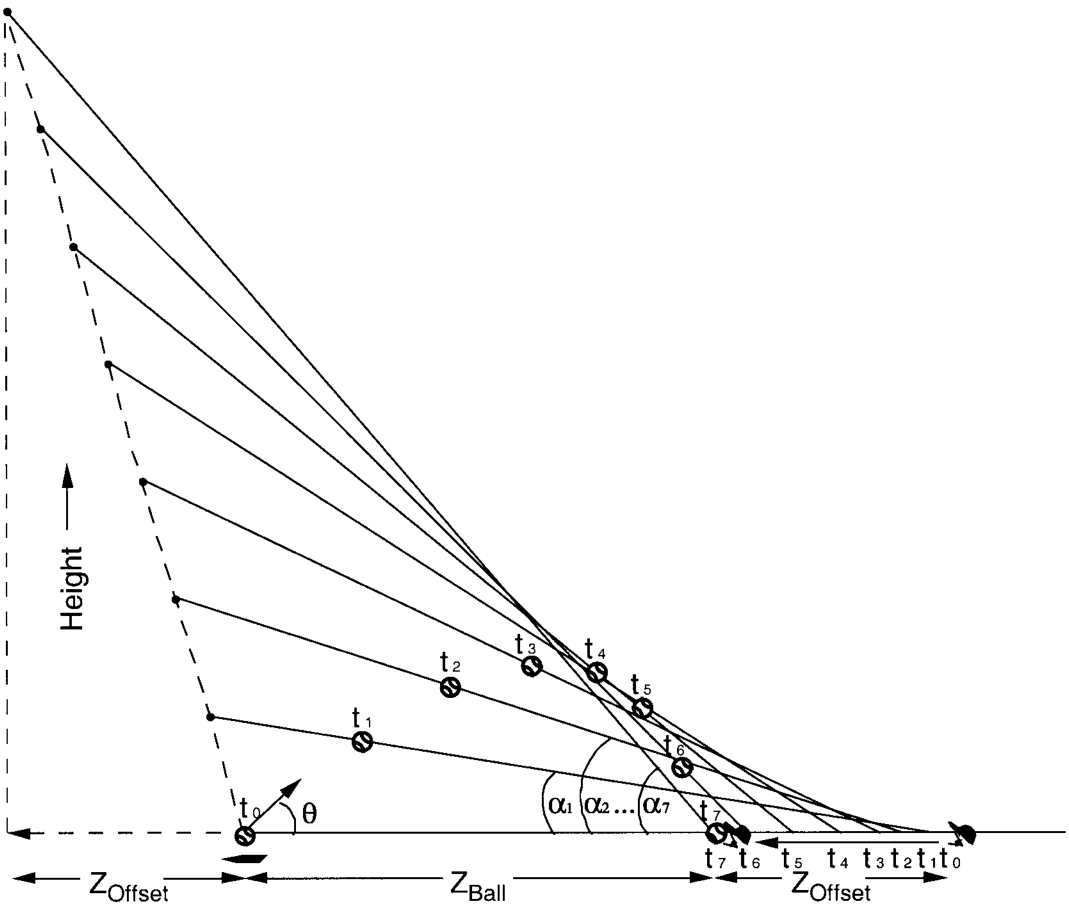

Figure 2. The optical acceleration cancellation (OAC) model. A side view of a fielder intercepting a fly ball in equal temporal intervals. The figure shows a ball trajectory (with air resistance) and the fielder approaching from the right while maintaining OAC. The tangent of the vertical optical angle increases at a constant optical speed when the fielder is on a collision course as shown. t = time; Z = depth distance.

portion of the optical trajectory for which the LOT strategy is being used and to test when OAC with alignment breaks down relative to a LOT. A minimum criterion of 95% was chosen to correspond to the $p < .05$ level of significance typically used in the field of psychology. The resulting curvature for these partial optical trajectories accounted for a mere 3.8% of the variance. We suggest that rather than rejecting the LOT strategy and its 95% of the variance, it would be more fruitful to explain the downward curvature and its 3.8% of the variance. In short, the portions of the trajectories that were statistically analyzed were very linear.

Downward Optical Curvature Tells the Fielder That the Ball Will Land in the Hemisphere in Front of the Destination Point to Which the Fielder Is Headed

McBeath et al. (1995a) and Shaffer and McBeath (2002) have indicated that upward curvature of the optical ball trajectory will cue fielders that the ball will land behind the destination to which they are running. As a result of examining balls hit beyond fielders in more detail, it has become clear that it is unusual for them to continue to run along paths such that the ball travels over their heads. This occurs, for example, when the fielders continue to face forward and maintain alignment or otherwise run too far laterally. Figure 4 shows theoretical examples when alignment is retained and the optical trajectories curve upward. Although this can occur, Shaffer and McBeath (2002) showed that, in general, fielders do not maintain lateral alignment with the ball while attempting to catch it. What occurs much more commonly is that fielders fall short of alignment and rotate their head and body (i.e., where they are looking) such that at some point the ball no longer is headed behind them but off to their side. At that point, the optical trajectory begins to curve outward and downward and continues to indicate that the fielders need to run further to that side. Thus, the downward optical curvature is not a disconfirmation of the LOT strategy but rather is an indication that fielders have rotated their reference frame so that the ball is then headed to land in the hemisphere in front of their destination point.

Because the fielders rotate their reference frames so that the ball is then headed to land in front of them, the LOT strategy provides

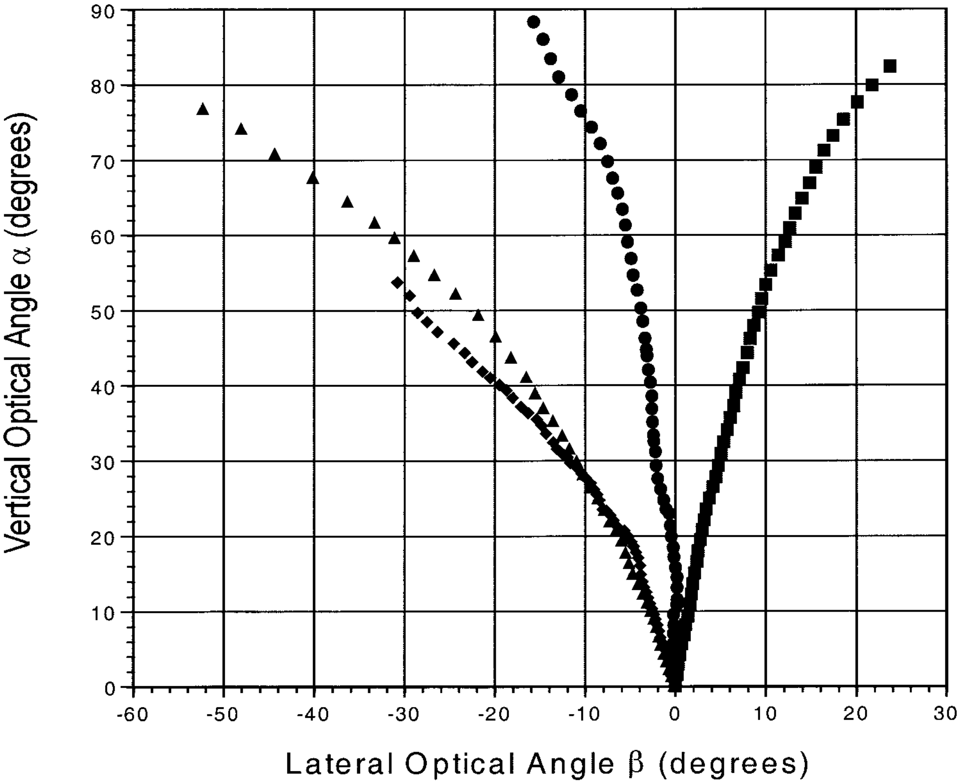

Figure 3. Examples in which the ball is headed too far over the head of the fielder. These are the initial portions of empirical optical trajectories during which a linear optical trajectory (LOT) is maintained to a degree that accounts for 95% of the variance and limited to a vertical optical angle of 90°. Successive ball positions are depicted sequentially rising in 1/30-s increments. The optical path exhibits slight outward curvature, indicating a lateral running path component that is somewhat short of an ideal LOT but well short of (and much more incongruent with) maintaining lateral alignment.

a cue indicating to run forward and to the side to which the trajectory of the ball is curving. For example, the slight outward curvature seen in the optical trajectories in Figure 3 indicates that the fielder has chosen a running path such that the ball is headed further to the right than the fielder's destination point. This is one of the strengths of the LOT heuristic. It is a navigational strategy that is based on a viewer-centered reference frame and does not require the world-centered position and orientation information necessary to monitor and maintain lateral alignment.

Further Confirmation That the LOT Heuristic Cues Lateral Position for Missed Balls

We tested the constancy of both the OAC and LOT strategies when balls are headed a short distance beyond a fielder's starting position in the depth direction and when a fielder runs in the wrong direction laterally to catch the ball. We did this to further examine the manner in which the optical trajectory curves outward and downward even for balls landing behind and off to the side of the fielder's initial starting position. We had fielders run left when the ball was headed to their right and run right when the ball was headed to their left. They were instructed to run in the opposite direction of the ball as soon as the ball was launched out of a pitching machine. We analyzed eight trials in which fielders ran in the opposite direction from where the ball was headed. Figure 5 shows two trials, one in which the ball is headed left (left) and one in which the ball is headed right (right). The top two graphs show the entire optical trajectory until near the point when the ball physically reaches the ground. The two graphs in the middle show the optical trajectory (i.e., the LOT) for the portion for which a LOT accounts for 95% of the variance in optical ball movement. The two graphs on the bottom are the vertical optical tangents of the ball plotted against time (i.e., OAC). We plotted the data for which both strategies no longer accounted for 95% of the variance in optical ball movement.

The first notable finding is that once again, balls landing beyond the initial fielder position resulted in optical trajectories that curved out and down and eventually descended to the ground as the ball landed. Consistent with the previous findings for missed balls, even when the fielder intentionally ran the wrong way, the LOT cue still indicated that the ball was headed to land in the hemisphere in front of the fielder's final orientation, cuing the fielder to run forward toward the correct destination in order to catch the ball. The second notable finding is that even though the ball landed beyond the initial fielder position, the vertical tangent decelerated, providing an OAC cue to run forward. This is because, like the LOT strategy, OAC is also based on a viewer-

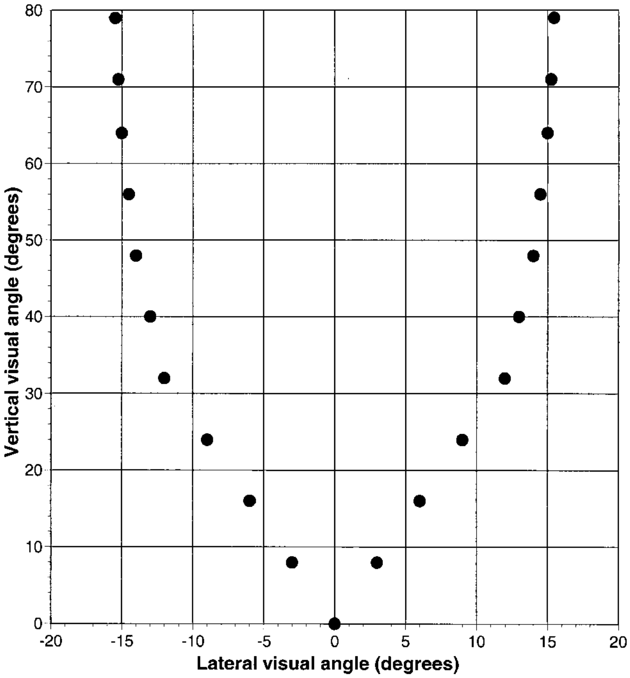

Figure 4. Two cases (one to the right and one to the left) are shown in which the optical trajectory curves upward for a ball headed beyond a fielder. These cases occur when the fielder maintains lateral alignment, so he or she ends up running underneath the ball as it goes over his or her head. When alignment is maintained with balls headed beyond the fielder, the vertical optical angle, α, accelerates more than the lateral optical angle, β (causing the optical ball trajectory to curve upward).

centered geometry, so as the fielder rotates his or her reference frame, the image of the ball eventually descends in front of him or her.

The same diminished vertical movement that causes the optical trajectory to curve downward also eventually causes the optical tangent to decrease. Both optical strategies operate in accordance with the rotating perspective of the observer, rather than a world-based mapping of space. This can be difficult to imagine without seeing the optical trajectories produced by the data in these situations because people's conscious perceptions of the world seem to be most often tied to a world-based reference frame.

The LOT Strategy Specifies Matched Rates of Change in the Lateral and Vertical Optical Angles for Both Catchable and Uncatchable Fly Balls

The LOT strategy specifies that fielders select a lateral optical angle, β, that matches the rate of change in the vertical optical angle, α. Thus, α plotted against time and β plotted against time should look similar in how they are shaped for both catchable and uncatchable balls, with possibly a slight lag for changes in β. We present independent graphs of α against time and β against time in Figure 6 for four trajectories where fielders attempted to catch the ball but could not quite catch it. Figure 6 shows that α and β appear to change simultaneously and that changes in one are highly correlated with changes in the other, as they diverge away from straight lines. Three of these trajectories are from Figure 3 in this article, and the fourth is an optical ball trajectory that lands too far in front of the fielder, from Shaffer and McBeath (2002). Changes in α significantly predict changes in β for each of the trajectories, all Fs > 37, all ps $< .001$. This supports the theory that the fielders run in a manner to link proportional changes in β to changes in α and thus maintain a LOT. The graph on the bottom right of Figure 6 shows α plotted against time and β plotted against time, as the fielder is running in to catch the ball that lands in front of him or her. The fielder is making changes while running in, slowing down, and running in again, until the ball begins to fall to the ground. As the fielder does this, α and β increase together, flatten out together, flatten out at a different rate together, increase again together, and then decrease together, all the time maintaining a LOT, until the fielder can no longer keep the ball from optically descending toward the ground. This shows graphically how fielders select their running path to scale the lateral optical ball movement to the vertical optical ball movement as the LOT theory predicts.

Discussion and Summary

One of the primary reasons why McBeath et al. (1995a) proposed and tested a strategy separate from OAC for cases in which balls are headed to the side is that fielders commonly report that these are easier to catch than ones headed straight toward them (Shaffer & McBeath, 1997). McBeath et al. (1995a) wanted to establish a ball-catching heuristic that explains how adding the extra complexity of a third spatial dimension can make that task of catching easier. One of the strengths of the LOT strategy is that it shows how adding information (i.e., the lateral optical angle β) to the vertical optical angle, α, can simplify the task for fielders by adding the spatial cue of linearity. Others have acknowledged the importance of accounting for lateral movement by at least coupling OAC with a separate lateral strategy like lateral alignment (Chapman, 1968). Yet, no strategy other than LOT has been put forward to explain why the task of catching fly balls headed to the side seems easier than catching those headed straight toward the fielder.

Although there has been some debate about the range of the generality of the LOT strategy for interception, alternative lateral strategies have not been proposed (McLeod, Reed, & Dienes, 2001). Meanwhile, numerous studies with humans, animals, and robots support complementary usage of the LOT and OAC strategies for navigation to intercept targets headed off to the side (McBeath et al., 1995a; McBeath, Shaffer, & Sugar, 2002; Shaffer, Krauchunas, Eddy, & McBeath, in press; Shaffer & McBeath, 2002). Studies using mathematical and robotic simulations confirm the viability of the LOT and OAC strategies, and they verify that observed errors are consistent with perceptual thresholds and reasonable control variable parameter settings (Aboufadel, 1996; McBeath et al., 2002; Sugar & McBeath, 2001; Suluh, Sugar, & McBeath, 2001).

In this article, we provide further support for use of the LOT strategy when a fielder is pursuing uncatchable balls headed beyond the fielder's initial position. We explain how when fielders

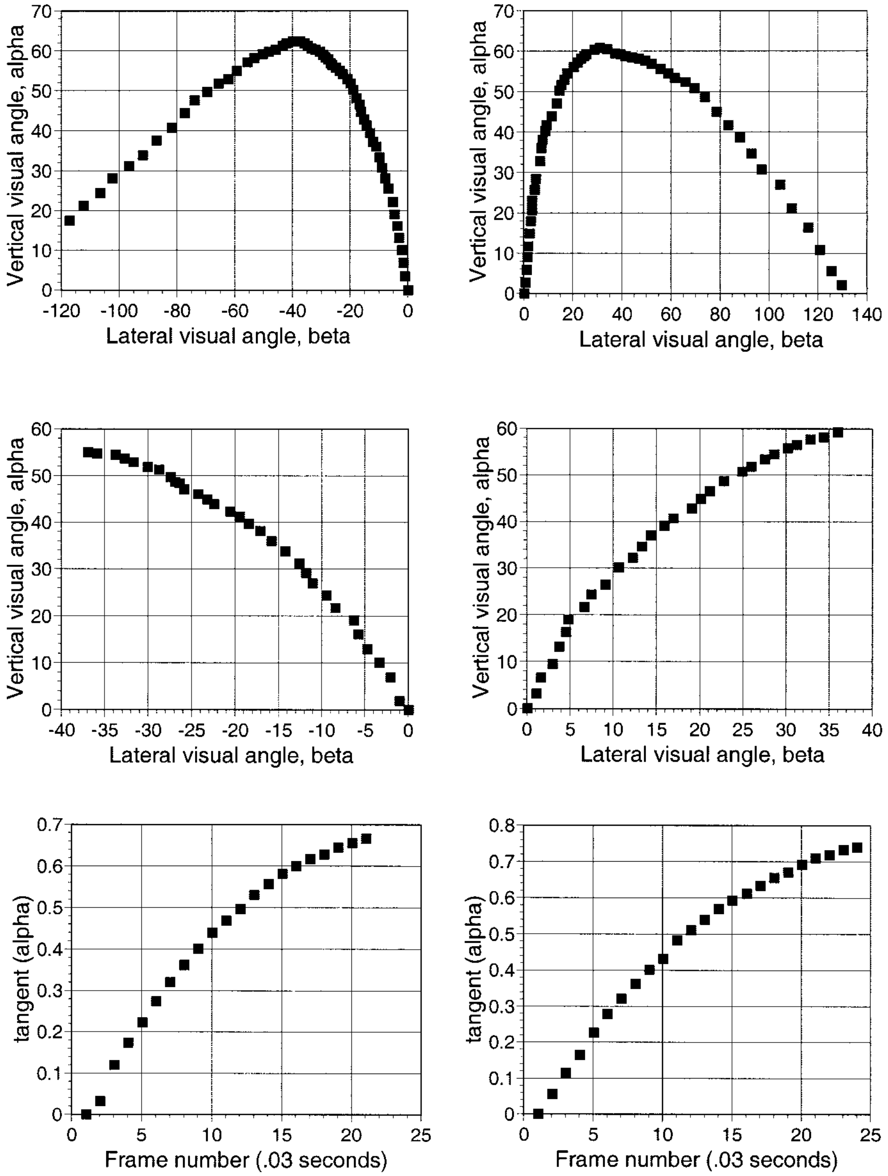

Figure 5. Plots of optical trajectories for optical acceleration cancellation (OAC) and a linear optical trajectory (LOT) when fielders are running in the wrong direction (left vs. right) to catch the ball. Two trials are shown in which the ball is headed left (shown to the left) and right (shown to the right). The entire optical trajectory is shown at the top, and the portions for which LOT (middle row) and OAC (bottom row) accounted for 95% of the variance are also shown.

pursue balls that go over their heads, upward optical curvature can be induced by maintaining alignment. Yet, as McLeod et al. (2002) noted, this upward curvature does not occur. This provides disconfirming evidence for maintenance of lateral alignment. Instead, fielders typically choose running paths and rotate their reference frames to keep the ball in front of them. This results in downward optical curvature, indicating that the ball is headed to land in the hemisphere in front of where the fielder is then directed. As a rule, the fielders select a lateral running path that exceeds lateral alignment for balls headed to land in front of them and falls short of lateral alignment for balls headed beyond them, in both cases initially maintaining a LOT. For balls headed beyond the initial fielder position, the same fielder reorientation that produces downward optical curvature also eventually leads to deceleration of the vertical optical tangent. Because the LOT and OAC strategies are viewer-based, both provide information indicating where the ball is headed relative to the fielder's orientation and destination. The current work shows how examination of open-loop failure conditions supports that fielders try to maintain the same optical control mechanisms even when interception is unachievable. The LOT strategy accounts for the consistent close matching of lateral to vertical optical ball movement, even for uncatchable balls, and it

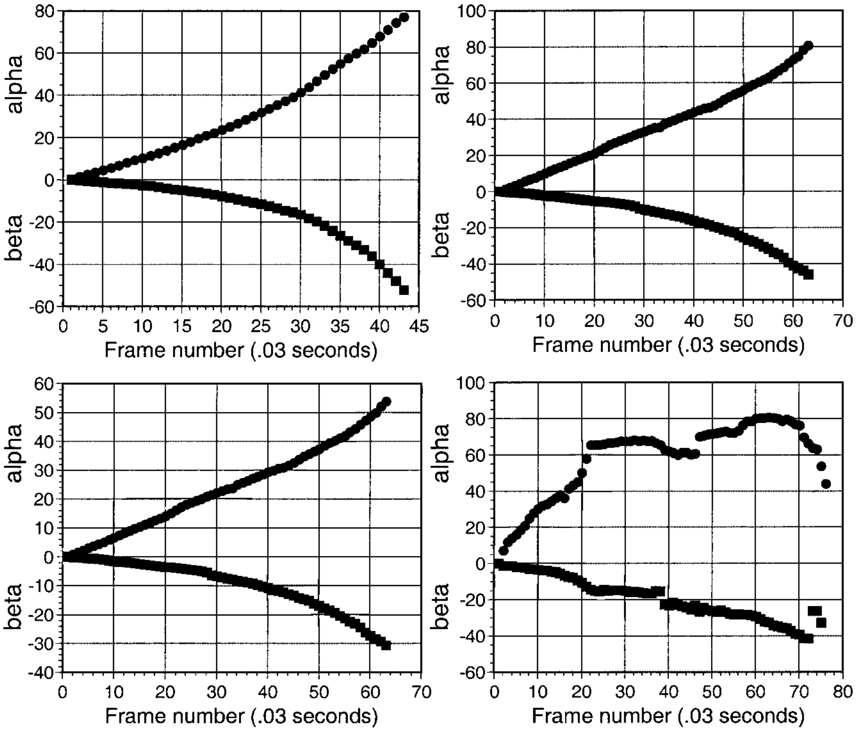

Figure 6. Graphs of vertical optical angle, α, against time and lateral optical angle, β, against time for four trajectories where the ball was not caught. The panels illustrate the close correspondence between changes in α and changes in β.

explains why balls headed to the side seem easier to catch than ones headed directly toward the fielder. In short, it has a lot going for it.

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Received September 10, 2002
Revision received February 20, 2003
Accepted April 29, 2003 ■