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Barry Cipra

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Michael K. McBeath,* Dennis M. Shaffer, and Mary K. Kaiser

PSYCHOLOGY

Catching Fly Balls: A New Model Steps Up to the Plate

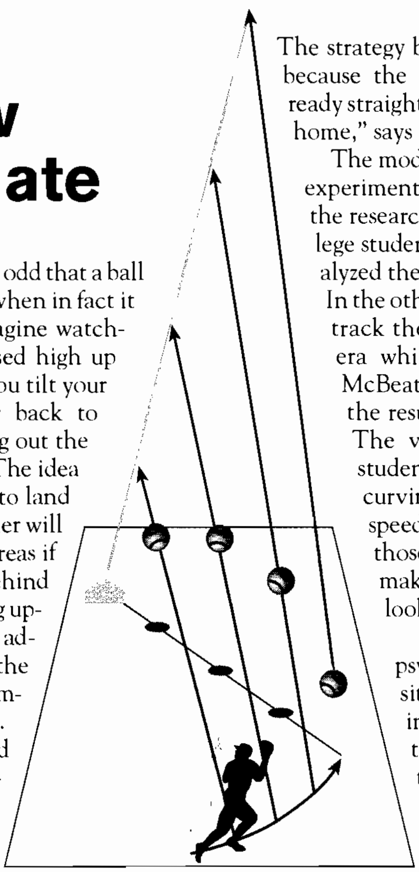
With the end of the baseball strike, fans will be spared the sight of replacement players bobbling balls and bungling plays. There is one area, however, in which even the replacement players could have done an acceptable job: catching routine flies to the outfield. In fact, even recreational players can chase down a lazy fly ball. How do players of average talent routinely manage to run to the right spot at the right time?

Like many skills, catching a fly ball is easier done than explained. But with the help of a mathematical model and some college students toting video cameras, psychologists Michael McBeath and Dennis Shaffer at Kent State University and Mary Kaiser at the National Aeronautics and Space Administration's (NASA's) Ames Research Center in Moffett Field, California, think they have uncovered the strategy every fielder uses without being aware of it. The key, they report on page 569 of this issue of *Science*, is to run so that the ball's trajectory looks straight. Do that—something that the human visual system is well equipped for—and you will end up in a spot where the ball will drop into your glove.

Joe Diestel, a mathematician and baseball enthusiast at Kent State, thinks the researchers have hit a home run. "It's a fascinating model, because it explains a number of lessons that you hear very early on if you're playing any kind of ball," he says. McBeath and his colleagues add that understanding the strategy might also turn out to be valuable in designing visual aids for, say, navigation in space.

In principle, there's no trick to tracking a fly ball. The ball's path across the sky contains more than enough information to guide you to the spot where it's going to land. A specially built robot could field balls by solving a relatively simple set of equations based on the observed curvature and acceleration. But outfielders running for a fly ball obviously don't have time for solving differential equations. Instead, they must have some rule-of-thumb strategy for interpreting the ball's path on the fly.

In 1968, Seville Chapman at Cornell Aeronautical Laboratory Inc. in Buffalo, New York, proposed that fielders head for the right spot by running along a path that cancels the apparent acceleration of the ball as gravity pulls it to Earth. In Chapman's model, an outfielder catches a fly ball hit directly at him by running forward or backward until the image of the ball is going straight up at a constant rate. (It may seem odd that a ball can appear to be going up when in fact it is falling to Earth, but imagine watching a ball that's been tossed high up and comes down at you: You tilt your head further and further back to keep the ball from escaping out the top of your field of view.) The idea is that if a ball is destined to land in front of him, the outfielder will notice it decelerating, whereas if it is destined to land behind him, he'll see it accelerating upward. Either way, he can adjust his position to cancel the acceleration and position himself directly under the ball.



Eye on the ball. By running so that the ball seems to fly upward in a straight line, a fielder is guaranteed to catch it.

Psychologists have raised doubts about this picture, however. They have pointed out that people's perception of acceleration is not good enough to account for their skill at shagging flies. Moreover, the acceleration model suggests that balls hit directly at an outfielder should be easier to catch than balls hit off to the side, because canceling the optical acceleration should be easiest for someone standing along the path of the ball. But experienced outfielders actually prefer to take a few steps to the side so they can get a "good look" at the ball, says Diestel, who coaches summer league baseball.

That's where McBeath's team takes the field. While he was pondering the optical acceleration model, McBeath recalls, a simpler strategy occurred to him: Run along a curving path, adjusting your speed and direction so that the apparent trajectory of the ball stays in a straight line (see figure). The strategy is as reliable as judging optical acceleration, says McBeath: "If you're running along a path that doesn't allow the ball to curve down, then in a sense you're guaranteed to catch it," because it always stays above you. And it may be more natural, curvature being something that the eye is good at perceiving. In fact, he adds, "that's a general approach for tracking and approaching things that's probably used by many organisms"—a possibility he and his colleagues say is supported by experiments with fish and houseflies.

Diestel points out that the psychologists' model can also explain why outfielders find balls hit straight at them difficult to catch: The strategy breaks down in that case because the optical trajectory is already straight. "Things like that strike home," says Diestel.

The model hit a home run in two experiments at Kent State. In one, the researchers videotaped two college students catching flies and analyzed the paths the students took. In the other, they had the students track the ball with a videocamera while running to catch it. McBeath and his colleagues say the results support their model The videos showed that the students tended to run along curving paths, varying their speed along the way, and that those paths had the effect of making the ball's trajectory look straight.

James Dannemiller, a psychologist at the University of Wisconsin who has investigated aspects of optical acceleration, is intrigued by the new model but is not yet ready to rule it foul or fair "There are a lot of different variables that you could conceivably use to get you to the right place [to catch a ba[ll]," he notes. "It's very difficult to determine which variable or variables the runner is actually using." But he adds that "the beauty of all these models is that people are finally pointing to variables that are actually there in optical stimulation." The models, he says, aim to "demystify what seems like a mysterious process."

None of these models, however, will do much to improve baseball, even at the amateur level. "Most of the errors that people tend to make are not that they can't get to the right place, but that the ball bounces out of their mitt or they close their eyes," McBeath observes. But Kaiser notes that NASA, which sponsored her research, isn' particularly concerned with catching baseballs anyway. What the aeronautics crowd is rooting for is a better understanding of how people use visual information for navigation Kaiser says: "The question is which sources [of data] seem to be the most useful and reliable for the human observer, and which ones do you need to preserve if you're creating a synthetic display [for example]?"

And on that kind of question, any help i welcome, even from amateur outfielders After all, when you're trying to dock a multibillion-dollar spacecraft, you don't want to have to come back to the dugout and admi to the manager that you misjudged the angle

–**Barry Cipra**

How Baseball Outfielders Determine Where to Run to Catch Fly Balls

Michael K. McBeath,* Dennis M. Shaffer, Mary K. Kaiser

Current theory proposes that baseball outfielders catch fly balls by selecting a running path to achieve optical acceleration cancellation of the ball. Yet people appear to lack the ability to discriminate accelerations accurately. This study supports the idea that outfielders convert the temporal problem to a spatial one by selecting a running path that maintains a linear optical trajectory (LOT) for the ball. The LOT model is a strategy of maintaining "control" over the relative direction of optical ball movement in a manner that is similar to simple predator tracking behavior.

Even recreational baseball outfielders appear to know virtually from the moment of bat contact where to run to catch a fly ball. In this task, the ball's approach pattern renders essentially all major spatial location and depth cues unusable until the final portion of the trajectory. Cues such as stereo disparity, accommodation, image expansion rates, and occlusion help to guide final adjustments in the interception path (*1*, *2*). During most of the task, the only usable information appears to be the optical trajectory of the ball (the changing position of the ball image relative to the background scenery). Conceivably, outfielders could derive the destination from an assumed projected parabolic trajectory, but research indicates that observers are very poor at using such a purely computational approach (*3*). In addition, factors such as air resistance, ball spin, and wind can cause trajectories to deviate from the parabolic ideal (*1*, *4*).

One proposed model is that outfielders run along a path that simultaneously maintains horizontal alignment with the ball and maintains a constant change in the tangent of the vertical optical angle of the ball, tan α (Fig. 1) (*5–9*). As the ball rises, tan α increases, but at a rate that is a function of the running path selected. If the fielder runs too far in (so that the ball will land behind him), $\partial(\tan \alpha)/\partial t$ will increase. If he runs too far out (so that the ball will land in front of him), $\partial(\tan \alpha)/\partial t$ will decrease. The fielder can arrive at the correct desti-

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nation by selecting a running path that keeps optical ball speed constant, achieving optical acceleration cancellation (OAC) of tan α. If the actual ball trajectory deviates somewhat from the parabolic ideal, OAC still works because it is an error-nulling strategy that couples fielder motion with that of the ball.

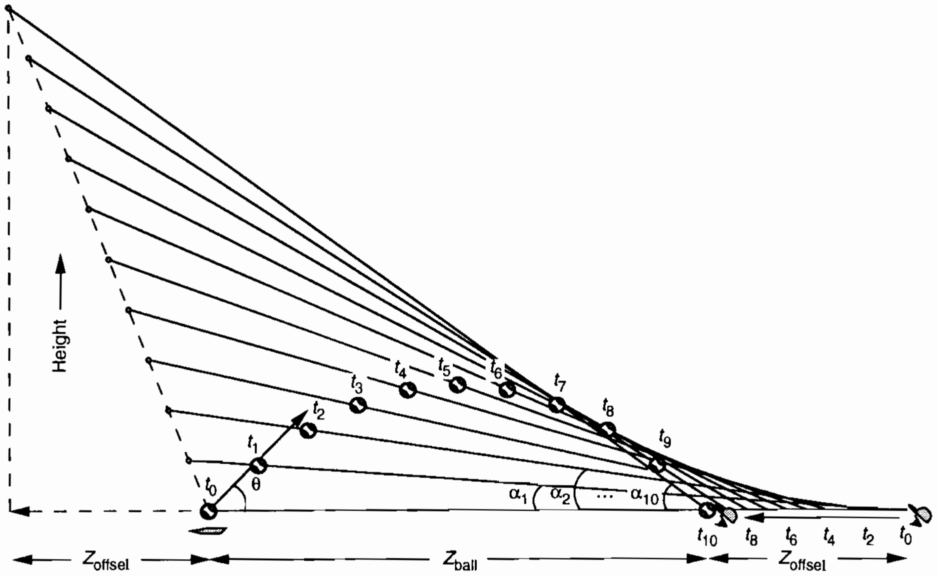

Fig. 1. The OAC model. The side view of a fielder running to catch a ball at times t_0 (initiation) through t_{10} (completion) is shown. The OAC model specifies that outfielders catch fly balls by running along a path that horizontally maintains alignment with the ball and vertically maintains constant optical ball velocity. Mathematically, the tangent of the vertical optical angle of the ball, tan α, increases at a constant rate, resulting in an optical ball trajectory that "never comes down." The optical path of the ball is identical to that of an imaginary elevator that starts at home plate, rises with a constant velocity, and is tilted forward or backward by the amount that the fielder is initially displaced from the ball's landing location (Z_{offset}). For ideal parabolic trajectories, the solution occurs when the fielder runs along a straight, constant-speed path that reaches the destination point at the same time as the ball.

The OAC model is elegant and has some empirical support (*6*, *7*), but it is flawed in several respects. First, the acceleration to be canceled is of tan α, not the vertical optical angle α itself. When $\partial(\tan\alpha)/\partial t$ is kept constant, $\partial\alpha/\partial t$ decreases (most noticeably as α becomes large), so the OAC model requires maintenance of an optical rate of change that is not constant but decreasing. Second, even if we assume that $\alpha \approx \tan\alpha$, OAC solutions require a precise ability to discriminate accelerations. Although there is some debate (*6*, *10*), empirical evidence generally indicates that people are poor at such tasks (*8*, *11*). In short, empirical evidence suggests that typical outfielders lack sufficient acceleration discrimination to account for their accuracy in catching fly balls.

The OAC concept of maintaining lateral alignment is also questionable because it assumes an orthographic, or planar optical projection, of the ball's location, whereas the projection is actually spherical. A spherical projection provides only optical angular information, and requires knowledge of distances to the ball and the background scenery in order to reliably determine lateral alignment. Because these distances are presumably unknown to the fielder, there is no way to determine the extent of perspective foreshortening that specifies lateral alignment with the ball.

Previous work examining the OAC model focused on balls hit directly toward the outfielder. The ball's lateral motion was assumed to be an irrelevant nuisance variable with little impact on catching performance, except possibly to make the task slightly more difficult (*5*–*8*). Presumably, having to take into account both vertical and horizontal motion parameters would be as difficult as or more so than accounting for vertical motion alone. Yet outfielders consider balls hit directly at them to be of a different type and to be harder to catch, not easier. We suggest that the case of a ball hit directly at the fielder is a special case (an aligned "accidental view") of the more general set of balls hit at various angles to either side. Outfielders appear to use their vantage outside the plane of the ball trajectory in a way that simplifies, rather than complicates, determination of ball destination.

We propose that the optical information available to the outfielder is more simply analyzed if it is not broken into separate vertical and horizontal components, but instead examined as a unified two-dimensional (2D) image. The geometry of the optical image is shown in Fig. 2, where α and β, respectively, specify the vertical and lateral optical angles between the ball and its initial optical location (home plate), and Ψ specifies the optical trajectory projection angle, or the observed angle of ball movement relative to the background horizon. To clarify, if a head-mounted camera were used, Ψ would be the angle of ball movement on the image. We propose that the outfielder selects a running path that maintains a linear optical trajectory (LOT) for the ball relative to home plate and the background scenery. A LOT is mathematically equivalent to keeping Ψ constant. As long as tan α and tan β are controlled so as to increase proportionally to each other over time, then tan Ψ (and hence Ψ) will remain constant ($\tan\Psi = (\tan\alpha)/(\tan\beta) = \text{constant}$). The solution is based on maintenance of balance between vertical and lateral optical angular change and requires no knowledge of distance to the ball or home plate.

As long as the fielder can preserve a LOT, he or she does not allow the ball to curve optically toward the ground. This requires that the fielder continuously move more directly under the ball, guaranteeing travel to the correct destination to catch it. The LOT strategy discerns optical acceleration as optical curvature, a feature that observers are very good at discriminating (*12*). If the fielder is running along a path so that the optical trajectory begins to decelerate vertically, it will manifest by curving down toward the fielder's front horizon. If the optical trajectory begins to accelerate vertically, it will manifest by curving up toward the zenith and arcing past the fielder toward his or her back horizon. Thus, maintenance of a LOT allows fielders to accomplish optical acceleration cancellation by "controlling" the shape of the ball trajectory image.

The initial trajectory projection angle Ψ is fully specified by the lateral angle at which the ball leaves the bat, but maintenance of other, similar projection angles will also work. To maintain a constant Ψ, the lateral and vertical optical components are not constrained to increase linearly, just proportionally to each other. Yet solutions with nonconstant optical speeds typically result in more running path curvature and more extreme running accelerations. Presumably, fielders would favor LOT solutions close to the one in which the components increase linearly, because solutions in this region keep the running path angle or bearing relatively constant and minimize overall running speed (*13*).

When a fielder must run to the side and change depth, he or she can maintain a constant increase in the tangent of the lateral optical angle, tan β, by leading the ball somewhat (scaling his lateral running speed to his distance from home plate). This results in LOT running path solutions in which the

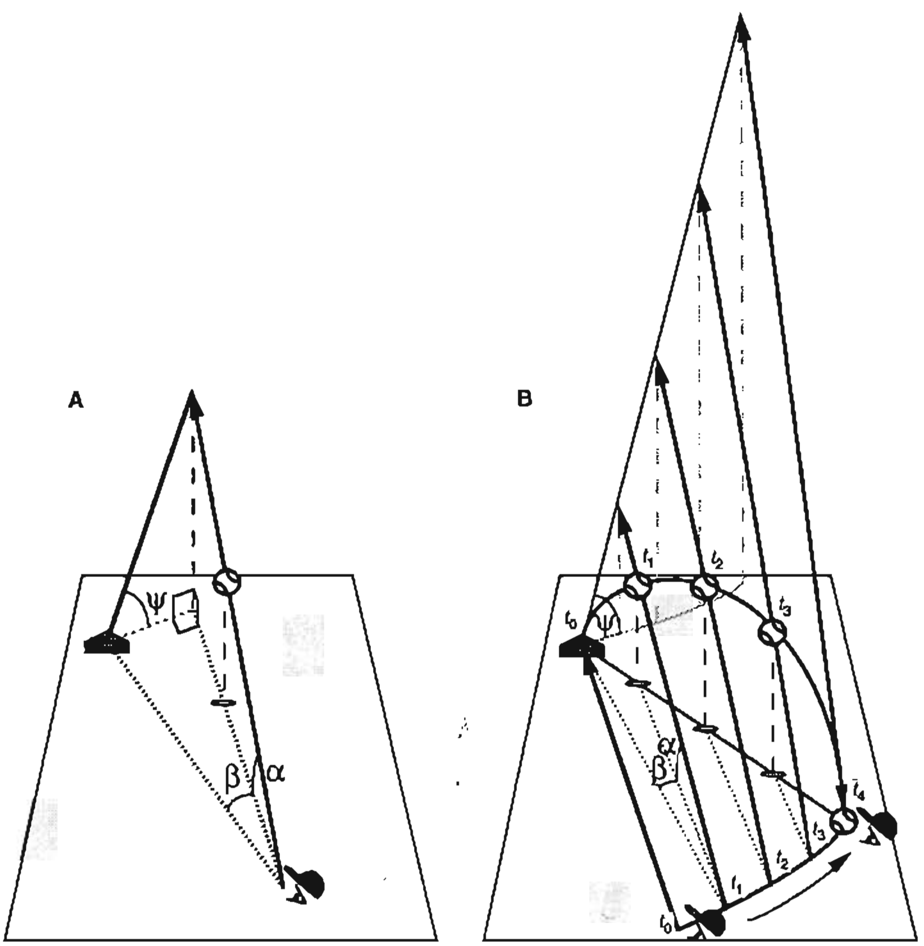

Fig. 2. The LOT model. This model specifies that fielders "control" the optical direction of ascent of the ball by adjusting their running path to null optical trajectory curvature. This keeps the image of the ball continuously ascending in a straight line throughout the trajectory. **(A)** Fielder optical angle geometry of a ball at an instant in midflight: α = vertical optical angle, β = horizontal optical angle, and Ψ = optical trajectory projection angle (angle from the perspective of the fielder that is formed by the ball, home plate, and a horizontal line emanating from home plate). The configuration of Ψ, α, and β forms a right pyramid such that $\tan \Psi = (\tan \alpha)/(\tan \beta)$. α and β are both controlled to increase continuously throughout the trajectory and are also labeled at time t_1 in (B). **(B)** Bird's-eye view of a fly ball with a running path that maintains a linear optical ball trajectory (positions shown at times t_0 through t_4). If the fielder maintains a constant increase in the lateral optical tangent, $\tan \beta$, he achieves approximate horizontal alignment with balls that are catchable. When he runs along a path so that both lateral and vertical tangents increase at a constant rate then the trajectory projection angle Ψ remains constant. Mathematically, the relation is expressed as

$$\tan \Psi = \frac{\tan \alpha}{\tan \beta} = \frac{C_\alpha f(t)}{C_\beta f(t)} = C_\Psi$$

where C_α, C_β, and C_Ψ are constants and $f(t) = t$ = time since trajectory initiation. In theory, $f(t)$ could be any monotonically increasing function, but for approximately parabolic trajectories, $f(t) = t$ leads to a relatively constant bearing and a near least energy running path. The fielder scales lateral running speed relative to his distance to home plate, which generally results in a running path that curves slightly. The resultant optical trajectory is represented behind the ball by the tilted line rising from home plate.

fielder accelerates, curves slightly beyond the ball, and decelerates somewhat as the destination point is approached.

If the ball trajectory deviates somewhat from the parabolic ideal, the LOT strategy still works. Like the OAC strategy, maintaining a LOT is an error-nulling tactic that couples fielder motion with that of the ball. The strategy therefore allows leeway to correct for perceptual error or changes in ball direction due to factors such as ball spin, air resistance, and gusts of wind.

In summary, the OAC model predicts that fielders select a running path that is straight with constant speed, resulting in a curved optical ball trajectory. The LOT model predicts that fielders select a running path that curves out with a ∩-shaped speed function, resulting in a linear optical ball trajectory.

We ran two experiments to evaluate the OAC and LOT models, each using two college students with some, but not extensive, outfield experience. In the first experiment, we mounted a video camera on a tower above and behind the fielders and videotaped their running paths. Fly balls were launched at a variety of angles at varying force from a distance of about 50 m. To optimize camera angle, balls were aimed so

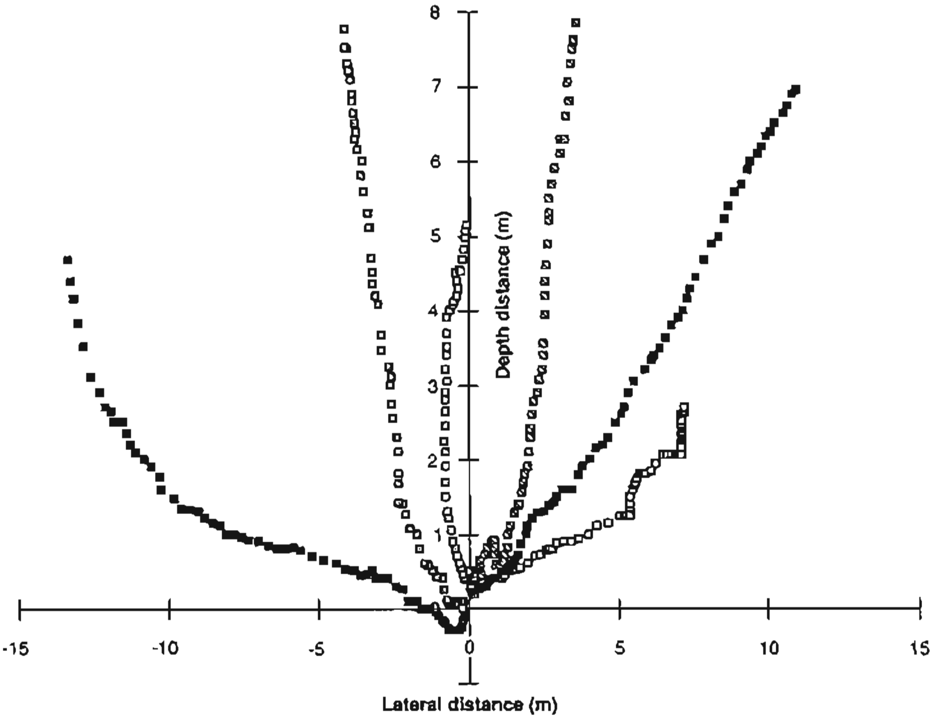

Fig. 3. Results of running path experiment. Top view of typical running paths with the origin and similarly patterned squares indicating initial and subsequent fielder positions at 1/30-s intervals. The observed running paths usually curve slightly and vary in speed as predicted by the LOT model.

that fielders ran forward in most trials. We coded 31 trials in which balls were caught. In three trials, the ball was launched directly toward the fielder. These were considered separately because running behavior seemed to be characteristically different, with more backtracking and unsystematic sideways movement. These movements may have been random anticipatory motion or possibly intentional attempts to induce lateral information. More trials of this type need to be examined to make a definitive statement, but our findings are consistent with the notion that these cases are an "accidental view" that may require an alternative strategy. Twenty-eight trials remained in the principal analysis. Distances run to catch fly balls ranged from 2 to 15 m in various directions.

Based on regression analyses, 71% of the running paths curved significantly as predicted by the LOT model ($z = 5.46$; $P < 0.001$) and 75% of the trials varied significantly in speed as predicted by the LOT model ($z = 5.89$; $P < 0.001$) (Fig. 3). Only 3% of the trials resulted in the constant-speed running behavior predicted by the OAC model. The pattern was the same for balls launched to the right and left. The general pattern of findings suggests that fielders were not maintaining lateral alignment as predicted by the OAC model but rather were circling beyond the ball as predicted by the LOT model.

In the second experiment, we examined the trajectory of the ball from the perspective of the moving outfielder. Here, the fielder carried a video camera on his shoulder that was aimed toward the ball while he ran to make the catch. The fielder stood about 50 m from the launch point, which was in front of a marked wall. Fly balls were launched at a variety of lateral angles at varying forces. In order to facilitate filming, most trials were aimed so that the fielder ran forward. For 31 trials, the fielder both caught the ball and kept the ball within view of the camera. Four of these trials were considered separately because the ball was launched directly toward the fielder, leaving 27 trials for our analysis. Position of the ball relative to home plate was measured on each video frame to determine both the trajectory projection angle Ψ and the optical speed of the ball.

Our findings revealed that optical speed exhibited a significant decline in 60% of the cases ($z = 4.22$; $P < 0.001$), refuting the hypothesis that fielders move to maintain a constant optical speed. Yet on median, a linear function accounted for over 99% of the variance of the tangent of the vertical optical angle, tan α. This confirms that fielders followed paths consistent with optical acceleration cancellation of tan α. Also, on median, a linear function accounted for 97% of the variance of the lateral tangent, tan β. Thus, the fielders chose paths with lateral change matching the vertical rate. This resulted in the LOT model or linear fit accounting for a median of 96% of the variance of the optical trajectory projection angle Ψ and additional quadratic curvature for under 2% (Fig. 4). The findings for both running paths and optical trajectories support the LOT model. The outfielders typically selected running paths that circled beyond the ball, had a $\cap$-shaped speed function, and maintained a linear optical ball trajectory.

This work supports the premise that outfielders use spatial rather than just temporal cues to initially guide them toward the fly ball destination point. It confirms that optical information can be simplified when analyzed as a full 2D image rather than separated into vertical and horizontal one-dimensional components. We suggest that the act of maintaining a linear trajectory takes advantage of a perceptual invariant—constancy of relative angle of motion—that can be used generically to pursue and approach moving objects (*14*). Airplane pilots are very accurate at spatial error-nulling tasks and perform particularly well in pursuit tracking tasks with displays that allow them to anticipate and maintain constant angular position relative to a target (*15*). Predators and organisms pursuing mates commonly adjust their position to maintain control of relative angle of motion between the pair. Tracking research with teleost fish (*Acanthaluteres spilomelanurus*) and houseflies (*Fannia canicularis*) indicates that they follow the motion of their target by maintaining an optical angle that is a function of direction of movement (*16*). Our findings suggest that baseball players use a similar spatial strategy.

The LOT model explains outfielder behavior well. Once an outfielder establishes a LOT solution, he or she knows he con-

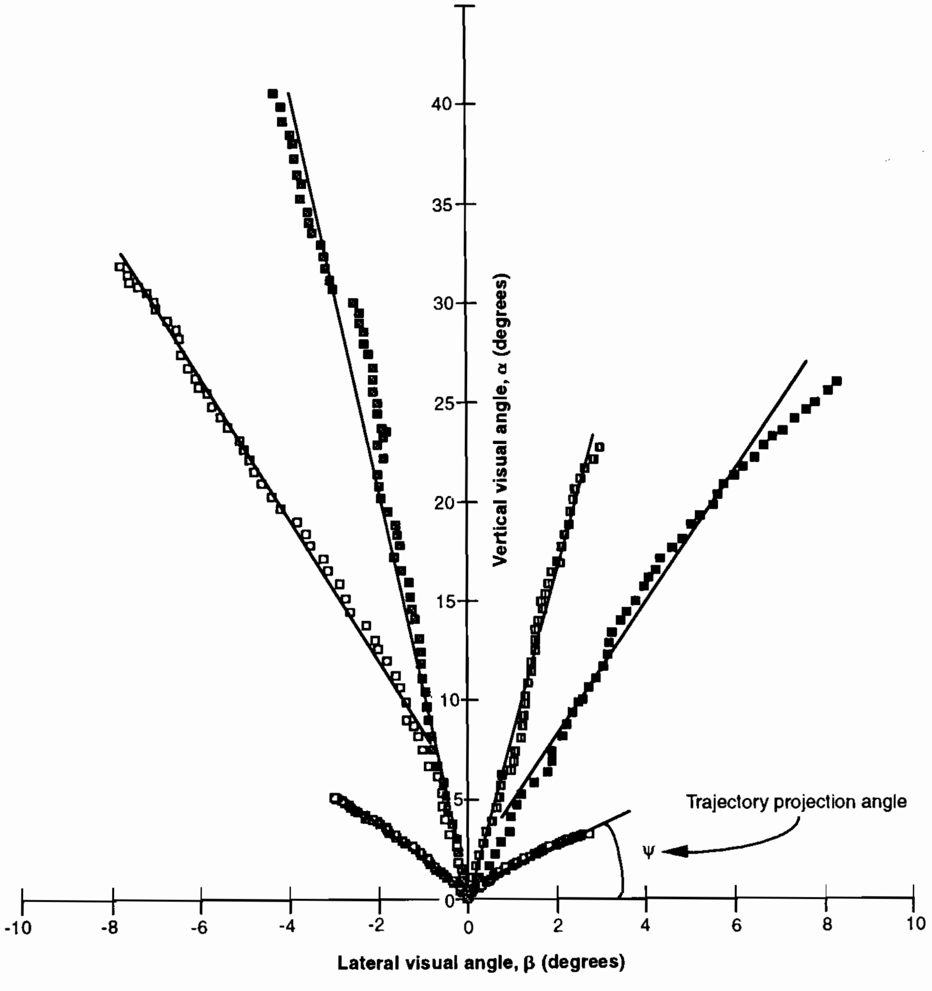

Fig. 4. Results of optical trajectory experiment. Fielder's view relative to home plate (origin) for typical examples of optical ball position at 1/30-s intervals up to the last half second. In general, the fielder maintained both vertical and horizontal OAC to achieve a LOT. The two trials that terminate at $\alpha \approx 5°$ visual angle are line drives, and the other four trials are high fly balls. The few deviations from continuously rising, straight-line trajectories are cases in which the fielder appeared to adjust and initiate a new linear optical direction partway through the trial (as occurred with the leftmost high fly ball shown).

trols the situation and will catch the ball, but he does not know when. This explains why fielders run into walls chasing uncatchable fly balls and why they do not rush ahead to the ball destination point, choosing instead to catch the ball while running. The LOT model explains why balls hit to the side are easier to catch. Fielders can use their robust ability to discriminate curvature rather than resorting to their weak ability to discriminate acceleration (*11*, *12*). It is also an error-nulling method that compensates for minor perceptual distortion or flight trajectory irregularity. In short, the LOT strategy provides a simple and effective way to pursue and catch a target traveling with approximately parabolic motion in three-dimensional space.

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