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Toward a Unified Fielder Theory: What We Do Not Yet Know About How People Run to Catch a Ball

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Linear optic trajectory theory claims that people catch balls by running in a direction that keeps an optic trajectory of the ball linear. The authors show a range of ball trajectories for which departures of the optic trajectory from linearity do not predict which direction people will run, and the direction they choose does not correct these departures. Data from a wide range of ball trajectories show that people run so that the angle of elevation of gaze to the ball increases at a decreasing rate. But it is not yet known why people choose the particular path they do from the many that would achieve this.

Thirty years have passed since the pioneering work of Chapman (1968) on how the information obtained from watching a ball that was hit into the air might control a fielder's interception strategy. Although there is general agreement about the control strategy used by fielders when running backward or forward to catch a ball thrown directly toward them, there is no consensus on the strategy used in the more general case in which the fielder must run to the side as well. Considering the ease with which some children learn to catch—just by watching ball flights and trying to catch the ball—this failure to discover what they learn is perhaps surprising.

The relation between a ball hit in the air and a fielder running to catch it can be described by the angles α and β in Figure 1. Alpha is the angle of elevation of gaze above the horizontal of the fielder watching the ball.[1] Given the position of the ball, the value of α at any moment defines a circle on the ground centered on the point where the vertical projection from the ball meets the ground (i.e., the locus of points from which the angle of elevation of gaze to the ball is α). Beta is the horizontal angle between a line from the fielder to the place where the ball started its trajectory and a line from the fielder to the point where the vertical projection from the ball meets the ground. Beta defines the point where the fielder is on the circle.

When a fielder watches a ball hit in the air, α will initially increase as the ball rises. If the ball is going to land in front and the fielder does not run forward fast enough, α will decrease, going to zero as the ball falls to the ground. If it is going to land behind and the fielder does not run backward fast enough, α will continue to increase, reaching 90° as the ball goes overhead. If the fielder runs so that α remains greater than zero but less than 90° throughout the flight, the ball will be successfully intercepted (McLeod & Dienes, 1996).

Beta starts at zero and initially increases (unless the ball comes directly toward the fielder). There is no strategy involving control of β that is either necessary or sufficient for successful interception. If the fielder approaches the arc of the ball from the side (as in Figure 1), β will continue to increase until the catch is made. If the fielder moves into line with the arc of the ball before it is caught, β will decrease, reaching zero when it is coming directly toward the fielder.

One theory of interception, derived from the work of Chapman (1968), assumes that the fielder's strategy is based on controlling α, because a necessary (and sufficient) condition for interception is that α is kept between 0° and 90° throughout the flight.[2] When catching balls coming directly toward them, fielders run backward or forward at a speed that allows α to increase throughout the flight but at a diminishing rate, which ensures that it never reaches 90°.[3] Because they do this by running at a speed that keeps the rate of increase of $\tan\alpha$ constant (i.e., its acceleration is zero; Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996) or by nulling the vertical acceleration of the optic trajectory of the ball (Michaels &

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[1] Fielders can track the progression of the ball by using a combination of eye, head, and body movements that keep the ball fixated or by monitoring the movement of the image across the retina (see Oudejans et al., 1999). Here we use α to mean the information available to the fielder about the elevation of the ball by whatever combination of cues it was obtained.

[2] Chapman's (1968) analysis showed how an object on a parabolic trajectory could be intercepted. It is not relevant to catching in games like cricket or baseball, as wind resistance produces large departures from parabolic flight for balls hit at the speeds encountered in these games (see Brancazio, 1985). However, the central fact that Chapman discovered also turns out to be true for the interception of balls on real world trajectories, so he is usually viewed as the originator of this approach.

[3] Some simple strategies, such as keeping α constant at the value it was when the fielder started to run, would keep α between 0° and 90° throughout the flight. The reason that efficient interception requires α to *increase* during the flight is explained in McLeod and Dienes (1996).

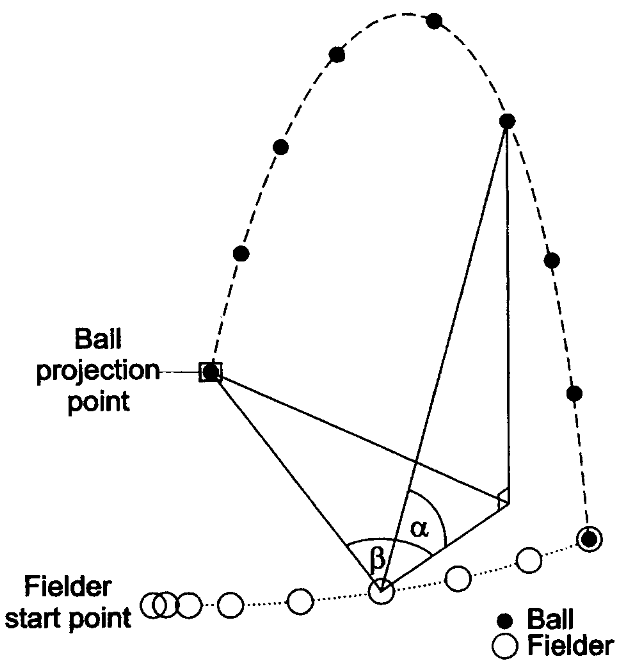

Figure 1. The positions of a ball and a fielder running to catch it at successive moments. The fielder runs to the right and slightly forward.

Oudejans, 1992), which is mathematically equivalent, this has become known as optic acceleration cancellation (OAC) theory.[4] At present, OAC theory only offers an explanation for how fielders choose an appropriate speed at which to run to control α. It offers no explanation for why they choose a particular path of the many that would achieve this. That is, it offers no explanation for the way that β changes as the fielder runs.

McBeath, Shaffer, and Kaiser (1995, 1996) observed a link between the changes in α and β as the fielder ran—for most of the flight the ratio $\tan\alpha/\tan\beta$ remained roughly constant. If changes in α and β are linked despite the fact that they describe independent aspects of the relationship between fielder and ball, this would suggest that the fielder chooses to run in a direction that causes the linkage. McBeath et al. postulated that a projection surface exists on which the image of the ball follows a path (the optic trajectory) with a direction defined by the ratio $\tan\alpha/\tan\beta$. If the ratio $\tan\alpha/\tan\beta$ remains constant as α increases, the optic trajectory will remain linear (McBeath et al., 1995, p. 570). And if the optic trajectory remains linear throughout the flight, the ball will be intercepted.[5] McBeath et al. proposed that fielders have access to the optic trajectory and run in a way that keeps it linear. In consequence, the ratio $\tan\alpha/\tan\beta$ remains constant. Hence, this is known as linear optic trajectory (LOT) theory. In principle, this theory is an advance over OAC theory because it offers a complete description for the fielder's behavior. That is, it explains why particular values of both α and β are produced as the fielder runs.

Thus, there are two contrasts between LOT and OAC theories. The first is the way they propose that fielders control α, the angle of elevation of gaze from fielder to ball. OAC theory suggests that they run so as to keep the rate of increase of $\tan\alpha$ constant. LOT theory suggests fielders monitor an optic trajectory and, by keeping this linear, indirectly control α. The second difference is the control of β. OAC theory makes no prediction about this. Interception is seen as involving control of α. But for LOT theory, control of β and α are inseparably linked. This is a strong prediction for LOT theory because although control of α is necessary and sufficient for interception, control of β is not. If α and β are linked in the way proposed by McBeath et al. (1995), this would be persuasive evidence in favor of LOT theory.

LOT theory is based on two empirical observations. First, for the catches analyzed by McBeath et al. (1995), the regression of $\tan\alpha$ on $\tan\beta$ had a significant linear component. That is, α and β increased as the fielders ran, but in such a way that the ratio $\tan\alpha/\tan\beta$ remained approximately constant. Second, the fielders did not usually run directly toward the place where the ball would fall but followed a slightly curved path. This curvature is predicted if the fielders run so that the ratio $\tan\alpha/\tan\beta$ remains constant. Although these two observations are *consistent* with LOT theory, they do not show that fielders are actively trying to maintain a linear optic trajectory as they run. In the following experiments, we test the theory directly by examining whether fielders choose a running path that nulls departures of the optic trajectory from linearity.

Experiment 1

Method

Subjects

These were 5 male cricket players and 1 female soccer goalkeeper (ages 18–51 years). All were of no more than enthusiastic amateur skill level at ball games.

Catching Task

We projected approximately 50 tennis balls from a height of 14.75 m to each fielder. They stood at ground level, starting 13.5 m horizontally from the ball's projection point. The experiment was conducted in the open air on a windless day. The fielders had their backs to the sun. The balls were projected in a random direction and with a range of horizontal and vertical velocities such that they fell unpredictably within a circle of radius ~10 m around the point where the fielder initially stood. Given the time of flight (1.4 s to 1.9 s), this gave a range including easy catches, catches that could just be caught running as fast as the fielders could, and catches that fell beyond the fielders' reach. We analyzed 165 successful catches.

One of the aims of the design of this (and the next) experiment was to use trajectories that increased the range of α and β in which catching behavior has been examined. By projecting balls off the roof of a building, it was possible to have relatively short flight times for balls going well to the side of the fielder. This gave some catches with much larger values of β than those in previous experiments and allowed us to have some

[4] Efficient interception requires that α increase as the fielder runs, but it must not reach 90° or the ball will go over the fielder's head. This may explain why fielders use a strategy that controls the rate of increase of a function of α ($\tan\alpha$), which increases more rapidly than α itself. If the rate of increase of $\tan\alpha$ is kept constant, α will increase at a diminishing rate and never reach 90°, so the ball will not go over the fielder's head.

[5] Maintaining a linear optic trajectory is not, in fact, a sufficient condition for ensuring interception. The trajectory must also be monitored to ensure that it continues to move in the same direction throughout the flight (Dannemiller, Babler, & Babler, 1996).

trajectories in which β was increasing more rapidly than α. The maximum values of α and β in this experiment were 80° and 71°, respectively. This contrasts with maximum values of 40° and 8°, respectively, in the catches reported by McBeath et al. (1995). Apart from the general desirability of increasing the range of α and β over which LOT theory has been tested, a problem with small angles is that $\alpha \approx \tan\alpha$. Thus, the data may not be adequate to distinguish whether the fielder is controlling α or $\tan\alpha$. With larger angles, it is easier to discriminate between these two possibilities.

Analysis of the Fielder's Position

The position of the fielder was recorded on video film taken from the ball projection point, 14.75 m above the ground. The positions on film were converted to positions on the ground by recording the position on film of a fielder standing at a matrix of points 2 m apart laterally and in depth covering the area in which the fielders ran. A curve-fitting program was applied to these known positions to generate a polynomial mapping function that inverted the quasi-trapezoidal representation on the video film back to the rectangular representation on the ground. The fielders' positions on the ground were determined by applying this mapping function to their positions on the video image. The camera covered a field of view ± 11° in depth and ± 30° horizontally around the fielder in the start position. When digitized, the image had an average density of 30 pixels/degree.

Analysis of the Ball's Trajectory

The position of the ball throughout each flight was computed using the method described by Brancazio (1985). The temporal duration of the flight and the distance the ball traveled were taken from the film, which recorded the start and finish of the flight and the position at which the ball was caught. These figures, combined with an estimate of the drag on a tennis ball at the velocities achieved in the experiment (Daish, 1972), were used to get a best fit for initial vertical and horizontal velocity. These were used to calculate the position of the ball throughout the flight. The position of ball and fielder were then used to calculate α and β at 40-ms intervals.

The accuracy of the trajectory calculation program was estimated in two ways. First, the terminal position of the ball on the film was compared with that estimated by the ball trajectory calculation program. The discrepancy between the two positions was never more than 7 cm. Second, a ball flight (extending 15.0 m with a maximum height of 4.1 m) was filmed from the side. The angle of gaze to the ball from the point where it fell was measured directly from the film. The angle of gaze from this point was also computed using the trajectory estimation program, to calculate the position of the ball. The error of the second method averaged less than 0.5° for the portion of the flight used in the analyses below (i.e., up to the last five frames).

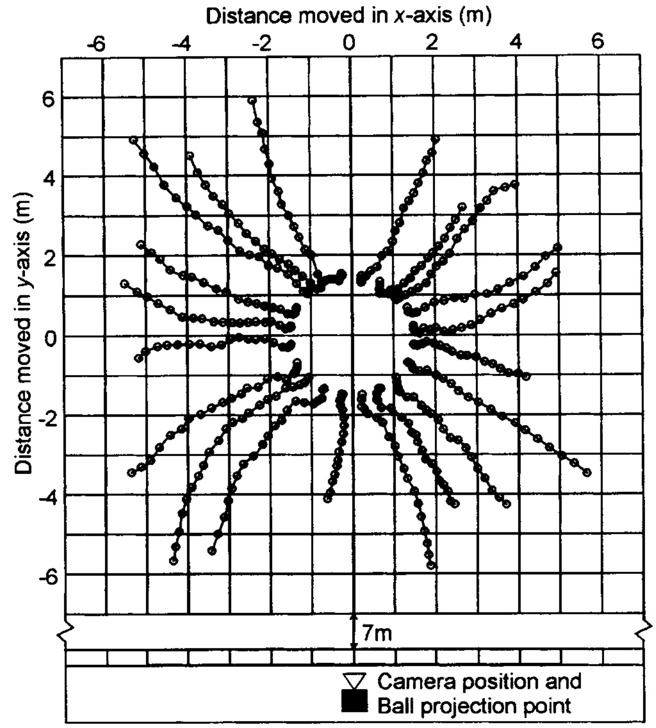

Figure 2. Typical running curves viewed from above. In reality, the fielders started from the same position every time, at (0, 0). The curves have been separated to make the earlier portions easier to see. They end at the point where the fielder caught the ball. The circles show the fielder's position at 80-ms intervals. The raw position data was smoothed by replacing each position p at time t, (P_t), by $0.5P_t + 0.25P_{t-1} + 0.25P_{t+1}$.

Results

Running Paths

Figure 2 shows typical running paths for the fielders. When they ran forward, 72 paths were concave toward the projection point, 5 were convex, and 20 were straight. When they ran back, 54 paths were convex toward the projection point, 2 were concave, and 12 were straight. (Concavity and convexity were determined by the curve of the running path from the point where the fielder passed the criterion for running, i.e., no further hesitations or reversals [see below], to the point where the ball was caught.) Therefore, we confirm McBeath et al.'s (1995) observation that the running paths are usually slightly curved, but note that the direction of curvature reverses when they run backward (McBeath et al., 1995, only presented running paths of fielders running forward). The paths are usually concave toward the projection point when they run forward and convex toward the projection point when they run backward.

Running Velocity—Left or Right and Backward or Forward

We analyzed the fielders' velocity separately for running left or right and backward or forward (these directions are defined in terms of the fielder's initial position, facing the projection point of the ball). Because fielders are not always motionless when waiting for the ball to appear and sometimes make an initial movement in the wrong direction, we set a criterion for running as the time at which they reached a speed of 50 cm/s in the correct direction and did not make a subsequent reversal or hesitation. A reversal was defined as reaching a speed of at least 50 cm/s in the wrong direction before moving in the correct direction; a hesitation was defined as slowing down by at least 50 cm/s, after having started in the correct direction, before resuming in the correct direction.

On average, fielders reached the criterion for running left or right 220 ms before they reached it for running backward or forward. The fielder reached the criterion for running left or right before reaching the criterion for running backward or forward for 161 out of 165 catches. There were 6 reversals and 1 hesitation in the left or right direction and 66 reversals and 69 hesitations in the backward or forward direction. It is clear that fielders decide whether to run left or right more quickly than they decide whether to run backward or forward.

McBeath et al. (1995) showed that LOT theory predicted curved running paths and thus presented them as evidence in favor of that theory. Our observations suggest an alternative explanation. Fielders usually start running left or right before they start running backward or forward. Therefore, they cover some of the lateral distance to the interception point before they start moving forward or backward toward it. Thus, the paths are concave toward the ball when running forward and convex toward the ball when running backward. Curved running paths may be a consequence of the greater salience of cues for running left or right than for those for running backward or forward, rather than a consequence of the control strategy used by the fielder.

Departure of the Optic Trajectory From Linearity

The tangent of alpha versus the tangent of beta. According to LOT theory, the fielder monitors the departure of the optic trajectory from linearity to decide which way to start running to intercept the ball—forward if the trajectory curves down, backward if it curves up. The optic trajectory is equivalent to the regression of $\tan\alpha$ on $\tan\beta$. We performed a multiple regression of $\tan\alpha$ on $\tan\beta$ from the time the ball appeared until the fielder started to run backward or forward (using the previously defined criterion for running). We confirm McBeath et al.'s (1995, 1996) observation—there was a large and significant linear component on every trial. That is, as α and β increase at the beginning of the flight, the ratio $\tan\alpha/\tan\beta$ remains roughly constant.

There was also a significant ($p < .05$) quadratic component (i.e., a departure from linearity) for 122 out of the 165 catches. On 44 of these, the fielder ran backward. The quadratic component was positive on 7 of these (i.e., the regression line curved up, indicating to the fielder, according to LOT theory, that he should run backward) and negative on 37 (i.e., the regression line curved downward, indicating to the fielder, according to LOT theory, that he should run forward). On a random sample of 44 of the catches on which he ran forward, the quadratic component was negative on all trials. Departure of the optic trajectory from linearity correctly predicts whether the fielder will run backward or forward on 51 (i.e., 7 + 44) out of 88 trials. This does not differ significantly from chance, $\chi^2(1) = 2.2$, $p > 0.1$. There was a wide range of initial values for the ratio $\tan\alpha/\tan\beta$. As the flight progressed, this ratio changed, but with the flight parameters used for these catches, it usually changed in the same direction. The departure from linearity of the ratio $\tan\alpha/\tan\beta$ (or, equivalently, the optic trajectory) does not predict in which direction the fielder will start running.

The tangent of alpha versus time. We repeated the technique using the regression of $\tan\alpha$ on time. According to OAC theory, the fielder runs in a way that keeps the rate of increase of $\tan\alpha$ constant. There was a significant quadratic component to the regression before the fielder started to run on 127 catches. On a random sample of 44 in which he ran backward, the quadratic component was positive on 41 (i.e., $\tan\alpha$ was accelerating, indicating to the fielder, according to OAC theory, that he should run backward) and negative on 3. On a random sample of 44 catches for which he ran forward, the quadratic component was negative on 40 (i.e., $\tan\alpha$ was decelerating, indicating, according to OAC theory, that he should run forward) and positive on 4. This pattern is significantly different from chance, $\chi^2(1) = 62.2$, $p < .0001$. OAC theory predicts fielders' behavior correctly on 81 out of 88 trials. In contrast, LOT theory did no better than chance.

Alpha versus beta. Although the condition for a linear optic trajectory is that the ratio $\tan\alpha/\tan\beta$ should remain constant as the fielder runs to catch the ball (McBeath et al., 1995, p. 570), proponents of LOT theory have sometimes suggested that the fielder may be keeping the ratio α/β constant (McBeath et al., 1996; Shaffer & McBeath, in press). We repeated the analysis using the regression of α on β before the fielder started to run backward or forward. Of the 68 catches in which the fielder ran backward, there were 65 in which there was a significant ($p < .05$) quadratic component to the regression. This was positive in one trial and negative in the remaining 64 trials. Of the 97 trials in which the fielder ran forward, there were 90 trials in which there was a significant quadratic component to the regression. It was negative on all trials. It is clear that there is nothing in the direction of change of the ratio α/β that can tell the fielder whether to run backward or forward.

The difference between the predictions of the two versions of LOT theory and OAC theory is illustrated in Figure 3. This shows eight catches selected at random from those with a significant value to the quadratic component of the regression of $\tan\alpha$ on $\tan\beta$: four in which the fielder ran forward and four in which the fielder ran backward. The data are shown from the time the ball appeared until the time the fielder reached the criterion for running. That is, the figure shows the information available to the fielder to decide whether to run backward or forward.

In the top panel of Figure 3, values for k and c have been selected such that $\tan\alpha = k\tan\beta + c$ for the first two data points (i.e., at $t = 0$ and 40 ms). (A value for c is required because α is approximately 45° at $t = 0$.) For subsequent data points, the graph shows the amount that the data depart from the straight line through the first two data points. If $\tan\alpha/\tan\beta$ remained constant, the data would lie along the line corresponding to 0 on the vertical axis. According to LOT theory, if the ball were going overhead, the line would curve up, and if it were going to fall in front, it would curve down, providing the fielder with the information about which way to run. It is clear that the direction of curvature offers no clue to the fielder about whether he should run backward or forward. It curves in the same direction whether the ball is going overhead or landing in front. In the middle panel of Figure 3, the equivalent analysis is performed for α and β. Again, it is clear that the direction of curvature of the optic trajectory defined as the ratio α/β offers no clue to the fielder about which way to run.

OAC theory claims that the fielder decides which way to run by the way that $\tan\alpha$ changes with time. In the lower panel of Figure 3, the relationship between $\tan\alpha$ and time is plotted in the same way. Values of k and c were chosen for the first two data points such that $\tan\alpha = kt + c$. Subsequent data points show the deviation from the straight line going through the first two points. If $\tan\alpha$ continued to change at a constant rate, the data would lie along the line corresponding to 0 on the vertical axis. It is clear that the change of $\tan\alpha$ with time offers a good clue as to whether the fielder should run backward or forward. If the ball is going overhead, $\tan\alpha$ accelerates; if it is going to land in front, $\tan\alpha$ decelerates.

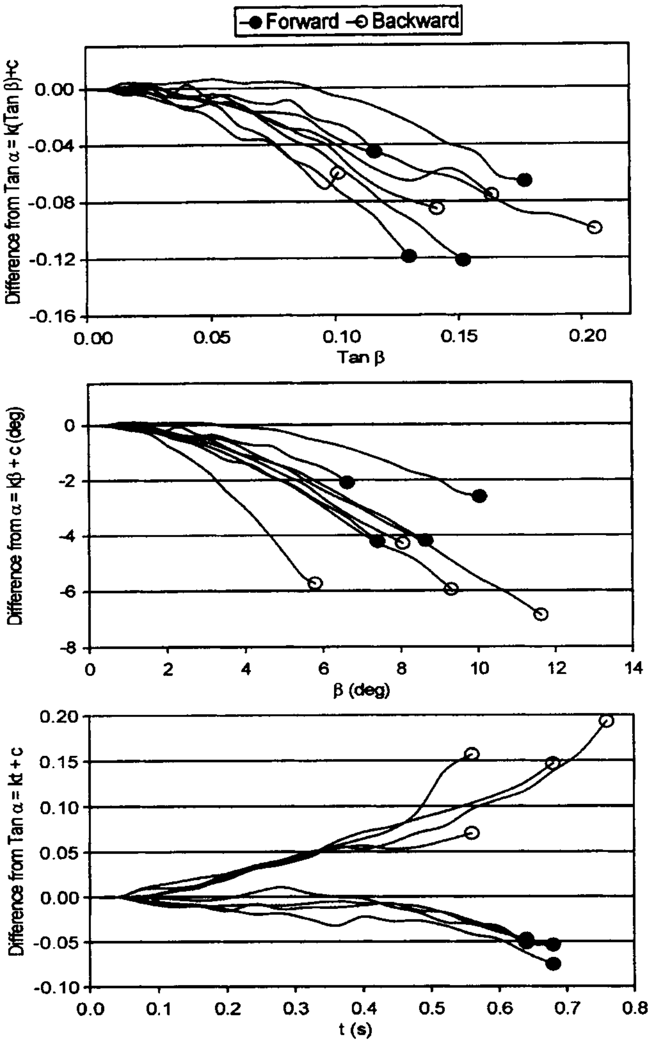

Figure 3. The relationship between tanα and tanβ (top panel), α and β (middle panel), and tanα and time (bottom panel) before the fielder started to run for catches in which the fielder subsequently ran forward (filled circles) or backward (empty circles). deg = degrees.

Linking of the Tangent of Alpha and the Tangent of Beta

For some catches, there was a significant quadratic component to the regression of tanα against time throughout the flight until shortly before the ball was caught. These were catches in which the fielders ran a little more slowly than the optimum and had to stretch out their hands in front of them (if running forward) or above their heads (if running backward) at the end of the flight to catch the ball, rather than taking it easily at eye level. LOT theory predicts that fielders will adjust their running on these trials in such a way that tanβ will change in the same way as tanα to maintain linearity of the optic trajectory.

We tested this prediction by selecting those catches in which there was a significant quadratic component for the regression of tanα on time for the flight up to 200 ms before the catch and by testing whether there was an equivalent quadratic component for the regression of tanβ on time.[6] When the fielder ran forward, there were 84 trials with a significant negative quadratic component to the regression of tanα against time. Of these, the regression of tanβ against time had a significant negative component on 25 trials, a significant positive component on 52 trials, and no significant component on 7 trials. When the fielder ran backward, there was a positive quadratic component to the regression of tanα on time in 67 trials. For these, there was a positive quadratic component to the regression of tanβ on time in 57 trials and a negative component in 10 trials. Overall, the prediction of LOT theory that changes in tanα and tanβ would be linked was correct on 82 out of 151 trials. This is no better than chance, $\chi^2(1) = 1.1$, $p > .25$.

Conclusion

We confirm McBeath et al.'s (1995) observation that there is a large linear component in the regression of tanα on tanβ for most catches. However, beyond the general tendency to increase, the changes in tanα and tanβ are not connected in the way predicted by LOT theory, nor do the changes provide the fielder with information about which way to run. Fielders' behavior appears to be based on allowing tanα to increase at constant velocity, as claimed by OAC theory, but this is not linked to control of tanβ.

LOT theory was developed on the basis of the behavior of fielders catching balls on trajectories that were unlike those used in this experiment. The balls in those experiments were hit on typical baseball trajectories from a distance of about 50 m. The result was values of α and particularly β that were considerably smaller than those in our experiment. It might be argued that because we used trajectories outside the range for which LOT theory was developed, the theory no longer applies, and that our observations should not be taken as evidence against the theory, in general, except for showing limits to its applicability. However, there is nothing in the geometry of LOT theory (see McBeath et al., 1995, Figure 2) that suggests the theory has limited applicability. The optic trajectory will appear whatever distance the ball is launched from and whatever the values of α and β. If the ball is going to land sufficiently far from the fielders to require them to move, they can do so in a way that keeps the optic trajectory linear if they wish. This was true for our fielders just as it was for McBeath et al.'s (1995).

There are two reasons for thinking that our fielders were not using a novel strategy despite the novelty of the trajectories. First, they had no difficulty deciding how to run. They started running within a few hundred milliseconds of the ball appearing (see Figure 2), just as they did in experiments such as McLeod and Dienes (1996), which used the sort of trajectories that outfielders would experience. Second, they produced curved running paths similar to those found by McBeath et al. (1995). This encourages the view that a single strategy is used for running to intercept a ball, irrespective of its trajectory.

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[6] A change in the relation between visual cues and behavior often occurs shortly before the ball is caught (Michaels & Oudejans, 1992; McLeod & Dienes 1996). It appears that fielders use one strategy to get to roughly the right place to make the catch and a second for moving the hands into the precise position to intercept the ball. Here we are concerned with the former strategy, so we ignore the last few hundred milliseconds before each catch when the relation between tanα and tanβ often becomes highly irregular.

Experiment 2

The variables that underlie the fielders' interception strategy should behave in the same way, however far the fielder has to run—laterally or in depth—to take the catch. In contrast, there is no reason to expect consistency in a variable that is not controlling behavior. In Experiment 2, we used this logic to examine whether β is controlled in the way predicted by LOT theory. Each fielder repeatedly ran to catch balls on the same trajectory from a number of different starting positions. We compared the way that $\tan\alpha$ and $\tan\beta$ changed as they ran. According to LOT theory, fielders run so as to keep the optic trajectory linear. If the optic trajectory is linear, the ratio $\tan\alpha/\tan\beta$ remains constant. Thus, there should always be a close link between changes in $\tan\alpha$ and $\tan\beta$. If OAC theory is correct, the way that $\tan\alpha$ changes with time should be consistent for every catch, but there is no reason why changes in $\tan\beta$ should show a consistent pattern. There are many ways of running that would keep $\tan\alpha$ increasing at a constant rate, but these would produce different patterns of change in $\tan\beta$.

Method

Subjects

The subjects were 5 male cricketers (ages 24–52 years). They were competent but not highly skilled fielders.

The Catching Task

The task is shown in Figure 4. Balls were projected on a fixed trajectory, with a launch angle of 63° from the horizontal, from a ball-throwing machine at ground level. If not caught, the ball would land 13.9 m away from the machine after 2.9 s. Fielders started at random from one of the four labeled positions. These represented various combinations of distance from the catching position, both laterally and in depth. Position 1 required the fielder to run 3 m to the left and 4 m backward; Position 2 required running 3 m to the right and 2 m backward; Position 3 required running 4 m to the right and 4 m forward; and Position 4 required running 5 m to the left and 2 m forward. Each fielder took a catch from each of the four start positions in turn, and then repeated this sequence 10 times.

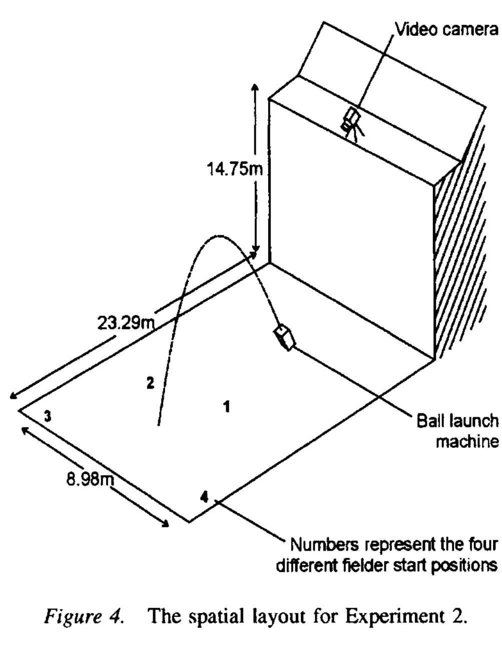

Figure 4. The spatial layout for Experiment 2.

The maximum values of α and β with these trajectories were 79° and 47°, respectively. In contrast to Experiment 1, the task was relatively straightforward and all balls were caught. Although much of the interest in catching strategy has been driven by the desire to understand the magical skill of a fielder who runs 20 yards and dives to catch a ball in a time window a few milliseconds wide before it hits the ground, most everyday catching is of objects that have been thrown toward the catcher with the intention that he or she *should* catch them. Indeed, it is with such catches that children learn to catch, and what they learn with these trajectories presumably forms the basis of their strategy when they try to take more difficult catches. Thus, the analysis of the strategy used to take easy catches is as important as the strategy used for those that are difficult.

Analysis of the Fielder's Position and the Ball's Trajectory

The fielder's running trajectory was recorded on a video camera mounted 14.5 m above the ground and 5.9 m behind the ball projection machine. The fielders' positions on video film were converted to real ground positions as described in Experiment 1. The ball's trajectory was computed as described in Experiment 1. From the position of the fielder and ball on each trajectory, α and β were calculated at 40-ms intervals.

Results

The Tangent of Alpha Versus the Tangent of Beta

We plotted $\tan\alpha$ and $\tan\beta$ against time for each catch. Both changed in an orderly way until just before the ball was caught (see Footnote 6). The sudden changes started when the fielder made symmetrical movements of both hands to catch the ball (cricketers running to catch the ball would always use two hands to catch the ball, if possible, because the use of a glove is prohibited in cricket), so we analyzed the data up to the point at which the fielder first made symmetrical movements of the hands.

Figure 5 shows how $\tan\alpha$ and $\tan\beta$ changed during the catch for each of the four starting positions. Each line represents the average value of $\tan\alpha$ or $\tan\beta$ across 10 catches for one fielder. The tangent of α increases at close to constant velocity throughout the flight, for every fielder and from all starting positions. The tangent of β starts increasing at constant velocity for all fielders (as predicted by LOT theory), but about half-way through the flight, the pattern changes. For some fielders, from Positions 3 and 4, $\tan\beta$ continues to increase. But for other fielders, it reaches a steady value. From Positions 1 and 2, for some fielders $\tan\beta$ reaches a steady value and for others it starts to decrease.

For every catch, we computed R^2 for the linear component of the regression of $\tan\alpha$ and $\tan\beta$ against time. This shows the extent to which $\tan\alpha$ and $\tan\beta$ increased linearly with time. We took the minimum value and the maximum value of R^2 for the 10 catches from each starting point for each fielder. Table 1 shows the interfielder medians of the minimum and maximum values. For every fielder, for every catch, independent of how far they had to run laterally or in depth, R^2 for $\tan\alpha$ against time was effectively 1. This is the finding of McLeod and Dienes (1993, 1996; Dienes & McLeod, 1993) and Michaels and Oudejans (1992) that formed OAC theory—fielders run at a speed such that $\tan\alpha$ increases at a constant velocity. In consequence, the angle of gaze increases at a decreasing rate, α is greater than 0° but less than 90° throughout the flight, and the ball is intercepted. For $\tan\beta$, the maximum value

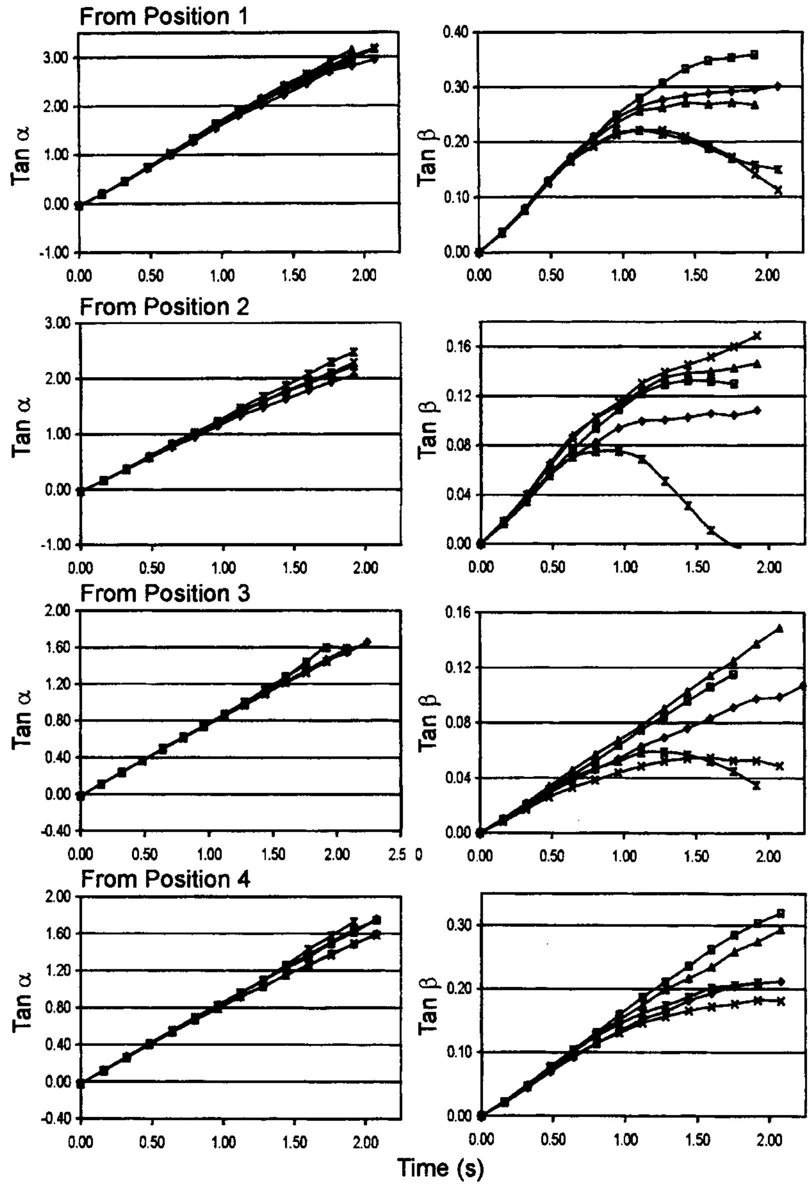

Figure 5. Changes in tanα and tanβ with time as fielders ran to catch the ball in Experiment 2. The rows show the four different starting positions (see Figure 4). The five curves in each box show the data of the 5 fielders. The data points are 160 ms apart.

of R^2 is also close to 1 from every start position (as predicted by LOT theory). This is a consequence of the fielder approaching the ball from the side so that β increased throughout the flight. But the minimum value depends on the starting position. For Positions 1 and 2 (at which the fielder had a small lateral distance to cover) the median minimum value is close to 0. On some flights, the fielder moved into line with the arc of the ball with the result that β went back toward zero and R^2 was low. (A single catch during which the fielder follows this pattern was analyzed by Jacobs, Lawrence, Hong, Giordano, & Giordano, 1996). Despite the fact that they were running from the same start position to catch a ball on the same trajectory, most fielders made at least one catch in which they approached the ball from the side (hence, the median maximum value of R^2 was close to 1) and at least one in which they were in line with the ball (so the median minimum value was close to 0). The mix of strategies from catch to catch varied from fielder to fielder, as can be seen from the range of average values in Figure 5.

The maximum median value of R^2 for tanβ from each start position is close to 1. This shows that most fielders were making at least one catch in which tanβ increased linearly with time. Therefore, data that supports LOT theory can be obtained from both short runs and longer runs. However, it is clear that the strategy that appears to support LOT theory by producing a linear increase in tanβ is adopted on some occasions but not others. Maintaining a linear optic trajectory is not a general strategy.

Table 1
R^2 for the Regression of the Tangent of Alpha and the Tangent of Beta Against Time

	tanα		tanβ	
Position	Minimum	Maximum	Minimum	Maximum
1	.98	1.0	.02	.96
2	.98	1.0	.04	.98
3	.99	1.0	.97	.99
4	.99	1.0	.23	1.0

Note. The rows indicate the position from which the fielders started (see Figure 4). The columns show the interfielder medians for the minimum and maximum values of R^2, across the 10 catches from each starting position.

It might be argued that in this experiment, the fielders could learn where the ball would fall and were running straight there. Hence, in the beginning they used one strategy based on watching the ball, and later they used another based on their knowledge of where the ball would land. A supporter of LOT theory might claim that this explains why the regression of tanβ against time was not always close to 1, as that theory predicts. We tested this possibility by determining whether there was a trend for R^2 for the regression of tanβ against time to change across the 40 catches for each fielder. If fielders were initially maintaining a linear optic trajectory, R^2 would start close to 1 but would fall as they learned where the ball would land and used this knowledge to run to the place where they expected it to land. Thus there would be a negative correlation between R^2 and time across the 40 catches. In fact, the correlations for all fielders were positive, although none were significantly different from zero. Thus there is no evidence that the fielders' strategy for the control of β changed in a systematic way as they experienced the ball's flight.

Alpha Versus Beta

McBeath and his colleagues (McBeath et al., 1996; Shaffer & McBeath, in press) have sometimes suggested that the optic trajectory that the fielder keeps linear is defined by the ratio α/β rather than the ratio tanα/tanβ. To investigate this possibility, we analyzed Experiment 2 in terms of α and β. Figure 6 shows the data for one fielder for each of the 10 catches from each of the four starting positions.

The individual fielder data offer no more support for this alternative version of LOT theory than the group data did for the standard version of the theory. From Positions 3 and 4, α and β both increased throughout the flight, but the ratio α/β did not remain constant. There was a pronounced quadratic component to the regression of α on β for 19 of the 20 catches. The ratio α/β decreased systematically as β increased. The catches from Positions 1 and 2 illustrate the same problem for LOT theory as the group data in Figure 5 and Table 1. Alpha increases throughout every flight, but after an initial increase, the behavior of β varies from catch to catch: sometimes it holds a constant value, sometimes it decreases, and sometimes it continues to increase. There is no suggestion that this fielder runs to keep the ratio α/β constant as a general strategy.

Conclusion

LOT theory claims that the fielder intercepts the ball by running in a way that keeps an optic trajectory linear. A linear optic trajectory will result in tanα and tanβ changing in the same way as the fielder runs. Although tanα always changes in the same way, increasing linearly with time, tanβ changes in a different way for different catches, for different fielders, and even for repeated catches of balls on the same trajectory by a given fielder. The inevitable conclusion is the strategy that ensures interception involves control of α but not of β.

It could be argued that the trajectories in these experiments are unlike those for which LOT theory was developed, and therefore the results should be cited as evidence for the limitations of LOT theory rather than as evidence against LOT theory in general. However, as in Experiment 1, we would counter that the optic trajectory proposed by LOT theory does not depend on the distance at which the ball was hit. The balls generated optic trajectories that the fielders could keep linear if they chose. In Experiment 1, the trajectories we used were novel—balls thrown off the top of a building. In this experiment, the trajectories, similar to a pop-up in baseball, would be commonly encountered by our subjects when fielding close to the bat in cricket. They are also the sort

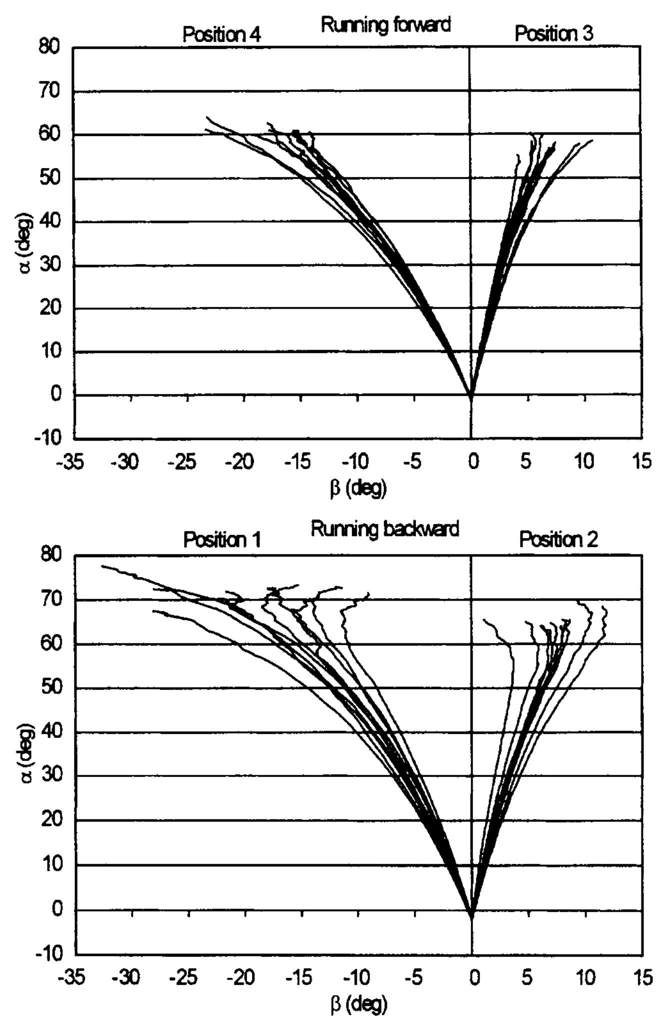

Figure 6. The relationship between α and β for 10 catches by one fielder, from each of the four starting positions shown in Figure 4. Individual data points are not shown. The traces are drawn through data points at 40-ms intervals. deg = degrees.

of trajectories that children experience when they learn to catch; when they master the skill of catching, they expand the range of balls they try to catch. If the strategy learned at short distances enables catching at longer distances, why would they abandon the strategy and learn a new one? A final reason that we believe the strategy used to take these catches is not outside the range LOT tries to explain is that the fielders sometimes produce data that are consistent with LOT theory (see Table 1). But, as the data make clear, this is an optional strategy, not a general one. Why fielders sometimes produce data that are consistent with LOT theory and why they sometimes do not is not yet clear.

General Discussion

One aspect of catching behavior now seems beyond doubt: When people run to catch a ball, they do so in a way that results in their angle of elevation of gaze to the ball increasing at a decreasing rate. This has been shown for people catching balls lobbed toward them from a short distance (Michaels & Oudejans, 1992; Oudejans, Michaels, Bakker, & Davids, 1999) and for people catching balls hit from a longer distance more typical of those experienced by outfielders in games like cricket or baseball, in which the balls are hit both directly toward the fielder (McLeod & Dienes, 1996) and to the side of the fielder (McBeath et al., 1995). In this article, we confirm that this is true when people run to catch balls hit to the side over shorter distances than the distances in the previous experiments (Experiment 2). We also show this is what people do in a situation that they may not have met frequently before (e.g., in which the ball is thrown off the top of a building; Experiment 1). Running at a speed that causes the angle of elevation of gaze to increase at a decreasing rate appears to be universal behavior when people catch a ball, at least for those with a reasonable level of skill.

We and others have assumed that this reveals the nature of the interception strategy (Dienes & McLeod, 1993; McLeod & Dienes, 1996; Tresilian, 1995). We have assumed angle of gaze forms the input to a servomechanism that produces a running speed such that the angle of gaze increases at a decreasing rate. If the angle of gaze increases too quickly or too slowly, the servo adjusts the fielder's speed accordingly. It would not be surprising if this were the strategy, because it guarantees interception (provided the fielder can run fast enough). Indeed, this is the strategy that genetic connectionist networks discover when they are given the angle of gaze they would get if they watched balls thrown toward them as input and acceleration toward or away from the ball as output, and are left to find an interception strategy for themselves (McLeod & Maass, in press). It is of course possible that some other strategy is involved, and the result that the angle of gaze increases at a decreasing rate is a by-product of that strategy and not the driving force behind it. This was the proposal of McBeath et al. (1995).

The predictions of LOT theory have not been supported by our data, therefore OAC remains the best account yet of catching behavior. However, OAC theory leaves an obvious question unanswered. When the ball is hit to the side of the fielder, many running paths will allow the angle of gaze to rise at a decreasing rate. Why do fielders choose a particular one? McBeath et al. (1995) proposed that they choose a path that keeps the ratio $\tan\alpha/\tan\beta$ constant. As we have shown, this sometimes happens, but it is not the general solution. However, we have no better suggestion to offer. Indeed, the results of Experiment 2 suggest why an answer to this question has been so hard to find. Fielders follow paths that produce different values of $\tan\beta$ on different occasions, even when running to the same place. Sometimes they get in line with the arc of the ball (and the regression of $\tan\beta$ onto time is curved), and sometimes they approach the arc of the ball from the side (and the regression of $\tan\beta$ onto time is linear). This article may seem negative as it shows where LOT theory fails but does not offer a positive alternative. However, we hope that the detailed analysis of where LOT theory is incorrect has cleared the ground for the discovery of the correct solution. We understand how α is controlled but not β. The Unified Fielder Theory awaits us.

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