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Towards a unified fielder theory: What we do not yet know about how people run to catch a ball

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Abstract

LOT theory claims that people catch balls by running in a direction which keeps an optic trajectory of the ball linear. We show a range of ball trajectories for which departures of the optic trajectory from linearity do not predict which direction people will run, nor does the direction they choose 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 why they choose the particular path that they do from the many that would achieve this, we do not yet know.
Towards a unified fielder theory: What we do not yet know

about how people run to catch a ball

Thirty years have passed since the pioneering work of Chapman (1968) on how the information obtained from watching a ball hit in the air might control a fielder’s interception strategy. Although there is general agreement about the control strategy used by fielders when running backwards or forwards to catch a ball thrown directly towards them, there is no consensus on the strategy used in the more general case when 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 $\alpha$ and $\beta$ in figure 1. $\alpha$ is the angle of elevation of gaze above the horizontal of the fielder watching the ball. Given the position of the ball, the value of $\alpha$ at any moment defines a circle on the ground centred 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 $\alpha$). $\beta$ 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 on the circle where the fielder is.

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Figure 1

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When a fielder watches a ball hit in the air $\alpha$ 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 $\alpha$ 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 back fast enough $\alpha$ will continue to increase, reaching $90^\circ$ as it goes overhead. If the fielder runs so that $\alpha$ remains greater than zero but less than $90^\circ$ throughout the flight the ball will be successfully intercepted (McLeod & Dienes, 1996).

$\beta$ starts at zero and initially increases (unless the ball comes directly towards the fielder). There is no strategy involving control of $\beta$ which is either necessary or sufficient for successful interception. If the fielder approaches the arc of the ball from the side (as in figure 1) $\beta$ 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 $\beta$ will decrease, reaching zero when it is coming directly towards the fielder.

One theory of interception, derived from the work of Chapman, assumes that the fielder’s strategy is based on controlling $\alpha$ since a necessary (and sufficient) condition for interception is that $\alpha$ is kept between $0^\circ$ and $90^\circ$ throughout the flight. When catching balls coming directly towards them fielders run backwards or forwards at a speed which allows $\alpha$ to increase throughout the flight but at a diminishing rate which ensures that it never reaches $90^\circ$. Since they do this by running at a speed which keeps the rate of increase of $\tan\alpha$ constant (i.e., its acceleration zero) (Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996) or, which is mathematically equivalent, by nulling the vertical acceleration of the optic trajectory of the ball (Michaels & Oudejans, 1992) this has become known as Optic Acceleration Cancellation (OAC) theory. At present, OAC theory only offers an explanation for how fielders choose an appropriate speed at which to run to control $\alpha$. It offers no explanation for why they choose a particular one of the many paths that would achieve this. That is, it offers no explanation for the way that $\beta$ changes as the fielder runs.

McBeath, Shaffer and Kaiser (1995, 1996) observed a link between the changes in $\alpha$ and $\beta$ as the fielder ran - for most of the flight the ratio $\tan\alpha/\tan\beta$ remained roughly constant.
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If changes in $\alpha$ and $\beta$ 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 which 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 $\alpha$ 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. 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 behaviour. That is, it explains why particular values of both $\alpha$ and $\beta$ 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 $\alpha$, 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 $\alpha$. The second difference is the control of $\beta$. OAC theory makes no prediction about this. Interception is seen as involving control of $\alpha$. But for LOT theory control of $\beta$ and $\alpha$ are inseparably linked. This is a strong prediction for LOT theory because while control of $\alpha$ is necessary and sufficient for interception, control of $\beta$ is not. If $\alpha$ and $\beta$ are linked in the way proposed by McBeath et al this would be persuasive evidence in favor of LOT theory.

LOT theory is based on two empirical observations. First, for the catches analysed by McBeath et al the regression of $\tan\alpha$ on $\tan\beta$ had a significant linear component. That is, $\alpha$ and $\beta$ increased as the fielders ran but in such a way that the ratio $\tan\alpha/\tan\beta$ remained
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approximately constant. Second, the fielders did not usually run directly towards 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
seeing whether fielders choose a running path which nulls departures of the optic trajectory
from linearity.

Experiment 1

Method

Subjects. These were five male cricket players aged 18 to 51 years and one female
soccer goal keeper. 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 stood initially. Given the time of flight (1.4 s to 1.9 s) this gave a
range from easy catches, through ones which could just be caught running as fast as they
could, to those which fell beyond their reach. 165 successful catches were analysed.

One of the aims of the design of this (and the next) experiment was to use trajectories
which increased the range of \( \alpha \) and \( \beta \) 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 \( \beta \)
than in previous experiments and to have some trajectories in which \( \beta \) was increasing more
rapidly than $\alpha$. The maximum values of $\alpha$ and $\beta$ in this experiment were 80° and 71° respectively. This contrasts with maximum values of 40° and 8° in the catches reported by McBeath et al (1995). Apart from the general desirability of increasing the range of $\alpha$ and $\beta$ over which LOT theory has been tested, a problem with small angles is that $\alpha = \tan \alpha$. Thus the data may not be adequate to distinguish whether the fielder is controlling $\alpha$ 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 to invert 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 digitised 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 travelled 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 (Daisch, 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 $\alpha$ and $\beta$ 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 (extent 15.0 m, max. height 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 < 0.5° for the portion of the flight used in the analyses below (i.e., up to the last five frames.)

**Results**

**Running paths**

Figure 2 shows typical running paths for the fielders. When they ran forward, 72 paths were concave towards the projection point, 5 were convex and 20 were straight. When they ran back, 54 paths were convex towards 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.) So we confirm McBeath et al's observation that the running paths are usually slightly curved, but note that the direction of curvature reverses when they run back (McBeath et al (1995) only presented running paths of fielders running forwards). The paths are usually concave towards the projection point when they run forward and convex towards the projection point when they run back.

**Running velocity left/right and backwards/forwards.** We analysed the fielders’ velocity
separately for running left/right and backwards/forwards (these directions defined in terms of the fielder’s initial position, facing the projection point of the ball). Since they 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 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/right 220 ms before they reached it for running backwards/forwards. The fielder reached the criterion for running left/right before reaching the criterion for running backwards/forwards for 161 out of 165 catches. There were 6 reversals and 1 hesitations in the left/right direction; 66 reversals and 69 hesitations in the backwards/forwards direction. It is clear that fielders decide whether to run left/right more quickly than they decide whether to run backwards/forward.

McBeath et al 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/right before they start running backwards/forwards. So they cover some of the lateral distance to the interception point before they start moving forwards or backwards towards it. Thus the paths are concave towards the ball when running forwards and convex towards the ball when running back. Curved running paths may be a consequence of the greater salience of cues for running left/right than for those for running backwards/forwards rather than a consequence of the control strategy used by the fielder.

Department of the optic trajectory from linearity
(i) \( \tan \alpha \text{ vs } \tan \beta \). 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 - forwards if the trajectory curves down, back 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 backwards or forwards (using the criterion for running defined previously). We confirm McBeath et al’s observation - there was a large and significant linear component on every trial. That is, as \( \alpha \) and \( \beta \) increase at the beginning of the flight the ratio \( \tan \alpha / \tan \beta \) remains roughly constant.

There was also a significant (\( p < 0.05 \)) quadratic component (i.e., a departure from linearity) for 122 out of the 165 catches. On 44 of these the fielder ran backwards. The quadratic component was positive (i.e., the regression line curved up indicating to the fielder, according to LOT theory, that he should run back) on 7 of these and negative (i.e., the regression line curved downwards indicating to the fielder, according to LOT theory, that he should run forwards) on 37. On a random sample of 44 of the catches on which he ran forwards the quadratic component was negative on all trials. Departure of the optic trajectory from linearity correctly predicts whether the fielder will run backwards or forwards 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, usually 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.

(ii) \( \tan \alpha \text{ vs time} \). We repeated the technique using the regression of \( \tan \alpha \) on time. According to OAC theory the fielder runs in a way which keeps the rate of increase of \( \tan \alpha \) constant. There was a significant quadratic component to the regression before the fielder
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started to run on 127 catches. On a random sample of 44 in which he ran back, the quadratic component was positive (i.e., \( \tan \alpha \) was accelerating, indicating to the fielder according to OAC theory, that he should run back) on 41 and negative on 3. On a random sample of 44 catches for which he ran forward the quadratic component was negative (i.e., \( \tan \alpha \) was decelerating, indicating, according to OAC theory, that he should run forwards) on 40 and positive on 4. This pattern is significantly different from chance (\( \chi^2 (1) = 62.2, p < 0.0001 \)). OAC theory predicts fielders’ behaviour correctly on 81/88 trials. In contrast, LOT theory did no better than chance.

(iii) \( \alpha \) vs \( \beta \). 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 maintaining the ratio \( \alpha / \beta \) constant (McBeath et al 1996; Shaffer & McBeath, 1999; Shaffer, personal communication). We repeated the analysis using the regression of \( \alpha \) on \( \beta \) before the fielder started to run backward or forward. Of the 68 catches in which the fielder ran backward there were 65 where there was a significant (\( p < 0.05 \)) quadratic component to the regression. This was positive in 1 trial and negative in the remaining 64. Of the 97 trials where the fielder ran forward there were 90 trials where 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 \( \alpha / \beta \) which 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 graphically 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 when the fielder reached the criterion for
towards a unified running. That is, it shows the information available to the fielder to decide whether to run backwards or forwards.

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**Figure 3**

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In the top figure 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 $\alpha$ is approximately $45^\circ$ at $t = 0$.) For subsequent data points the graph shows the amount by which 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 0.0 on the vertical axis. According to LOT theory, if the ball were going over head 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 over head or landing in front. In the middle figure the equivalent analysis is done for $\alpha$ and $\beta$.

Again, it is clear that the direction of curvature of the optic trajectory defined as the ratio $\alpha / \beta$ 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 figure 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 0.0 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 backwards or forwards. If the ball is going over
Linking of \( \tan \alpha \) and \( \tan \beta \)

For some catches there was a significant quadratic component to the regression of \( \tan \alpha \) against time throughout the flight until shortly before the ball was caught. These were catches where 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 head (if running back) 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 \( \tan \beta \) will change in the same way as \( \tan \alpha \) to maintain linearity of the optic trajectory.

We tested this prediction by selecting those catches when there was a significant quadratic component for the regression of \( \tan \alpha \) on time for the flight up to 200 ms before the catch and testing whether there was an equivalent quadratic component for the regression of \( \tan \beta \) on time. When the fielder ran forward there were 84 trials with a significant negative quadratic component to the regression of \( \tan \alpha \) against time. Of these, the regression of \( \tan \beta \) 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 back there was a positive quadratic component to the regression of \( \tan \alpha \) on time in 67 trials. For these there was a positive quadratic component to the regression of \( \tan \beta \) on time in 57 trials and a negative component in 10 trials. Overall the prediction of LOT theory that changes in \( \tan \alpha \) and \( \tan \beta \) would be linked were correct on 82 out of 151 trials. This is no better than chance \( (\chi^2(1) = 1.1, p > 0.25) \).

Conclusion

We confirm McBeath et al’s observation that there is a large linear component in the regression of \( \tan \alpha \) on \( \tan \beta \) for most catches. However, beyond the general tendency to
increase, the changes in tan$\alpha$ and tan$\beta$ 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’ behaviour appears to be based on allowing tan$\alpha$ to increase at constant velocity, as claimed by OAC theory, but this is not linked to control of tan$\beta$.

LOT theory was developed on the basis of the behavior of fielders catching balls on trajectories which 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 $\alpha$ and particularly $\beta$ which were considerably smaller than those in our experiment. It might be argued that by using trajectories outside the range for which LOT theory was developed that theory no longer applies, so our observations should not be taken as evidence against the theory in general so much as showing limits to its applicability. However, there is nothing in the geometry of LOT theory (see McBeath et al 1995, figure 2) which suggests that the theory has limited applicability. The optic trajectory will appear whatever distance the ball is launched from and whatever the values of $\alpha$ and $\beta$. If the ball is going to land sufficiently far from the fielders to require them to move they can do so in a way which keeps the optic trajectory linear if they wish. This was true for our fielders just as it was for McBeath’s.

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. This encourages the view that a single strategy is used for running to intercept a ball, irrespective of its trajectory.

Experiment 2
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The variables which 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 which is not controlling behaviour. In Experiment 2 we used this logic to see whether $\beta$ 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 which 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 five male cricketers aged 24-52 yr. 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 labelled 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 back; position 2, 3 m to the right and 2 m back; position 3, 4 m to the right and 4 m forward; position 4, 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.

The maximum values of $\alpha$ and $\beta$ 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 which have been thrown towards 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 that for those which are difficult.

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Figure 4

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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 in the way described in experiment 1. The ball’s trajectory was computed in the manner described in the previous experiment. From the position of the fielder and ball on each trajectory $\alpha$ and $\beta$ were calculated at 40 ms intervals.

Results

$tan \alpha$ vs $tan \beta$, $tan \alpha$ and $tan \beta$ were plotted 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 at the time that the fielder made symmetrical movements of his two 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 analysed the data up to the point where 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 ten catches for one fielder. \( \tan \alpha \) increases at close to constant velocity throughout the flight for every fielder from all starting positions. \( \tan \beta \) 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 it continues to increase. But for other fielders it reaches a steady value. From positions 1 and 2 for some fielders it 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 start point for each fielder. Table 1 shows the inter-fielder 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 1.00. This is the finding of McLeod & Dienes (1993, 1996; Dienes & McLeod, 1993) and Michaels and Oudejans (1992) which formed OAC theory - fielders run at a speed such that \( \tan \alpha \) increases at constant velocity. In consequence the angle of gaze increases at a decreasing rate, \( \alpha \) is greater than 0° but less than 90° throughout the flight and the ball is intercepted. For \( \tan \beta \) the maximum value
of $R^2$ is also close to 1.0 from every start position (as predicted by LOT theory). This is a consequence of the fielder approaching the ball from the side so that $\beta$ increased throughout the flight. But the minimum value depends on the starting position. For positions 1 and 2 (where the fielder had a small lateral distance to cover) the median minimum value is close to 0.0. On some flights the fielder moved into line with the arc of the ball with the result was that $\beta$ went back towards zero and $R^2$ was low. (A single catch where the fielder follows this pattern was analysed 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 where they approached the ball from the side (hence the median maximum value of $R^2$ was close to 1.0) and at least one where they got into line (so the median minimum value was close to 0.0). 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 $\tan \beta$ from each start position is close to 1.0. This shows that most fielders were making at least one catch where $\tan \beta$ increased linearly with time. So data which supports LOT theory can be obtained both from short runs and longer ones. However, it is clear that the strategy which appears to support LOT theory by producing a linear increase in $\tan \beta$ is adopted on some occasions but not others. Maintaining a linear optic trajectory is not a general strategy.

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It might be argued that in this experiment the fielders could learn where the ball would fall and were running straight there. Hence, early on they used one strategy based on watching the ball and later they use another based on their knowledge of the ball flight. A supporter of

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towards a unified LOT theory might claim that this explains why the regression of $\tan \beta$ against time was not always close to 1.0 as that theory predicts. We tested this possibility by seeing whether there was a trend for $R^2$ for the regression of $\tan \beta$ against time to change across the 40 catches for each fielder. If fielders were maintaining a linear optic trajectory to start with, $R^2$ would be close to 1.0 and would fall as they learnt where the ball would land and could 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 $\beta$ changed in a systematic way as they experienced the ball’s flight.

$\alpha$ vs $\beta$. McBeath and his colleagues have sometimes suggested that the optic trajectory which the fielder keeps linear is defined by the ratio $\alpha/\beta$ rather than the ratio $\tan \alpha / \tan \beta$ (McBeath et al, 1996; Shaffer & McBeath, 1999; Shaffer, personal communication). To check this possibility we analysed this experiment in terms of $\alpha$ and $\beta$. 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 starting positions 3 and 4 $\alpha$ and $\beta$ both increased throughout the flight but the ratio $\alpha/\beta$ did not remain constant. There was a pronounced quadratic component to the regression of $\alpha$ on $\beta$ for 19 of the 20 catches. The ratio $\alpha/\beta$ decreased systematically as $\beta$ increased. The catches from starting 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 $\beta$ 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 so as to keep the ratio $\alpha/\beta$ constant as a general strategy.
Conclusion

LOT theory claims that the fielder intercepts the ball by running in a way which keeps an optic trajectory linear. A linear optic trajectory will result in \( \tan \alpha \) and \( \tan \beta \) changing in the same way as the fielder runs. Although \( \tan \alpha \) always changes in the same way, increasing linearly with time, \( \tan \beta \) 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 that the strategy which ensures interception involves control of \( \alpha \) but not of \( \beta \).

It could be argued that the trajectories in these experiments are unlike those for which LOT theory was developed so the results should be cited as evidence for the limitations of LOT theory rather than evidence against LOT theory in general. However, as in experiment 1, we would counter that the optic trajectory proposed by LOT theory is not dependent on how far away the ball is hit from. These balls generated optic trajectories which the fielders could keep linear if they chose to. In experiment 1 the trajectories 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 of trajectories which children experience when they learn to catch. When they master the skill of catching they expand the range of balls they try and catch. If the strategy learnt at short distances works at longer distances, why would they drop it and learn a new one? A final reason for thinking that the strategy used to take these catches is not outside the range which LOT tries to explain is that the fielders sometimes produce data which is 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 which is consistent with
LOT theory and sometimes do not is not yet clear.

Discussion

One aspect of catching behaviour now seems beyond doubt: When people run to catch
a ball they do so in a way which 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 towards them from
a short distance (Michaels & Oudejans, 1992; Oudejans, Michaels, Bakker & Davids, 1999)
and for balls hit from a longer distance more typical of those experienced by outfielders in
games like cricket or baseball, both directly towards them (McLeod & Dienes, 1996) and
when they are hit to the side of the fielder (McBeath et al. 1995). In this paper we confirm that
this is true when people run to catch balls hit to the side over shorter distances than in the
previous experiments (Experiment 2). We also show that is what people do in an unusual
situation which they may not have met frequently before (where the ball is thrown off the top
of a building) (Experiment 1). Running at a speed which 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 that
angle of gaze forms the input to a servo-mechanism which 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 since it guarantees interception (provided the fielder can run fast enough).
Indeed, this is the strategy which genetic connectionist networks discover when they are given
the angle of gaze they would get if they watched balls thrown towards them as input,
acceleration towards or away from the ball as output and are left to find an interception strategy for themselves (Maass & McLeod, 1999). 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.

The predictions of LOT theory have not been supported by our data so OAC remains the best account yet of catching behaviour. 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 proposed that they choose a path which keeps the ratio $\tan \alpha / \tan \beta$ constant. As we have shown, this sometimes happens, but it is not the general solution. But 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 which 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 paper 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 $\alpha$ is controlled but not $\beta$. The Unified Fielder Theory awaits us.
References


Shaffer, D. & McBeath, D. (1999). Baseball outfielders use a LOT to track uncatchable fly balls. (Unpublished manuscript.)

Author notes

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Footnotes

1 Fielders can track the progression of the ball by a combination of eye, head and body movements which keep the ball fixated and/or by monitoring the movement of the image across the retina (see Oudejans et al 1999). Here we use $\alpha$ 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 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 which Chapman discovered turns out to be also true about 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 $\alpha$ constant at the value it was when the fielder started to run, would keep $\alpha$ between 0° and 90° throughout the flight. The reason why efficient interception requires $\alpha$ to increase during the flight is explained in McLeod and Dienes (1996).

4 Efficient interception requires that $\alpha$ increases 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 which controls the rate of increase of a function of $\alpha$ ($\tan\alpha$) which increases more rapidly than $\alpha$ itself. If the rate of increase of $\tan\alpha$ is kept constant, $\alpha$ 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. It must also be monitored to ensure that it continues to move in the same direction throughout the flight (Dannemiller, Babler & Babler, 1996).

6 A change in the relation between visual cues and behaviour 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 \( \tan \alpha \) and \( \tan \beta \) often becomes highly irregular.
Figure Captions

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.

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 \( 0.5P_t + 0.25P_{t+1} + 0.25P_{t-1} \).

Figure 3. The relationship between \( \tan\alpha \) and \( \tan\beta \) (upper), \( \alpha \) and \( \beta \) (middle) and \( \tan\alpha \) and time (lower) before the fielder started to run for catches in which the fielder subsequently ran forward (filled circles) or backward (empty circles).

Figure 4. The spatial layout for experiment 2.

Figure 5. The changes in \( \tan\alpha \) and \( \tan\beta \) 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 five fielders. The data points are 160 ms apart.

Figure 6. The relationship between \( \alpha \) and \( \beta \) for 10 catches by one fielder from each of the four starting positions shown in figure 4. To avoid undue clutter individual data points are not shown. The traces are drawn through points at data points at 40 ms intervals.
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Table 1

$R^2$ for the regression of $\tan \alpha$ and $\tan \beta$ against time

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<tr>
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<th>$\tan \alpha$</th>
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<td>4</td>
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Note. The rows indicate which position the fielders started from (see figure 4). The columns show the inter-fielder medians for the minimum and maximum values of $R^2$ across the 10 catches from each starting position.
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Figure 1
Figure 2
Numbers represent the four different fielder start positions
From Position 1

From Position 2

From Position 3

From Position 4
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