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The Generalized Optic Acceleration Cancellation Theory of Catching

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The generalized optic acceleration cancellation (GOAC) theory of catching proposes that the path of a fielder running to catch a ball is determined by the attempt to satisfy 2 independent constraints. The 1st is to keep the angle of elevation of gaze to the ball increasing at a decreasing rate. The 2nd is to control the rate of horizontal rotation necessary to maintain fixation on the ball. Depending on the lateral velocity of the ball relative to the fielder, this rate may be zero or constant at a negative or positive value. The authors show that a simulated fielder implementing the GOAC strategy follows a path indistinguishable from that of real fielders running to catch balls thrown on the same trajectories.

Keywords: catching, interception, optic acceleration cancellation (OAC), linear optic trajectory (LOT)

When people run to catch a ball, their angle of elevation of gaze (α) as they watch the ball increases at a decreasing rate (Dienes & McLeod, 1993; McLeod & Dienes, 1993, 1996; McLeod, Reed, & Dienes, 2001; Michaels & Oudejans, 1992; Oudejans, Michaels, Bakker, & Davids, 1999).[1] Chapman (1968) demonstrated mathematically that a fielder standing in the plane of flight of a ball on a parabolic trajectory would intercept it if he or she ran at a constant speed that kept the acceleration of the tangent of α at zero. If this were the fielder's strategy, it would explain the observation above, for if the acceleration of the tangent of α is zero, α will increase at a decreasing rate. This strategy can be interpreted as nulling the acceleration of the rising image of the ball, so it has become known as the optic acceleration cancellation (OAC) theory of catching.

McLeod and Dienes (1996) showed that Chapman's (1968) mathematical proof, with its unrealistic simplifying assumptions, was but the tip of a more general strategic iceberg. They demonstrated that there is no need for the fielder to compute the tangent of α. Any strategy that allows α to increase but does not let it reach 90° will lead to interception. Keeping the acceleration of the tangent at zero is just one way of achieving this more general goal. McLeod and Dienes also showed that the strategy would work for balls on real-world ballistic trajectories, not just for those on the parabolic flights analyzed by Chapman, and that interception does not require fielders to run at constant velocity.

Although allowing α to increase at a decreasing rate guarantees interception in principle, Tresilian (1995) showed that in practice, given the limited speed at which people can run, it would be an ineffective strategy when the fielder was not initially standing in the plane of the ball's flight. For effective interception, this method must be supplemented by a strategy that ensures that the fielder runs toward the plane of the ball's flight early in its trajectory. Chapman (1968) suggested that in addition to nulling the vertical optic acceleration of the ball, fielders should maintain horizontal alignment with the ball, but he did not provide empirical evidence that such a strategy was used. Tresilian (1995) explored a strategy whereby the fielder added a component to the running path determined by OAC strategy in proportion to the rate at which the visual tracking system had to rotate horizontally to fixate the ball, but he offered no empirical evidence that this strategy was used. Jacobs, Lawrence, Hong, Giordano, and Giordano (1996) suggested that fielders run laterally to reach the plane of the ball's flight before taking the catch and then use OAC strategy to control their movement backward or forward within the plane. They reported data from only one catch, so the generality of this strategy is unclear.

The decision about how to move toward the ball's flight plane appears straightforward. If the fielder's tracking system rotates horizontally anticlockwise as it follows the ball, the ball is going to the fielder's left, so the fielder should move left; if the tracking system rotates clockwise, the ball is going to the fielder's right, so the fielder should move right. This is such a simple, direct, and reliable cue that it would be natural for it to form part of the fielder's interception strategy. OAC theory has successfully explained how people catch balls coming directly toward them. In the present study, we propose a generalization of that theory (generalized optic acceleration cancellation, or GOAC, theory) to show how balls projected to the side are intercepted.

The way we have analyzed the information provided by horizontal rotation of the tracking system as the fielder fixates the ball is shown in Figure 1. The direction from the fielder's initial position (F_0) to the ball's start point (B_0) gives a reference direction against which the subsequent horizontal direction from fielder to ball is measured. The ball moves to the fielder's right (B_1), and the tracking system will rotate to the right before the fielder starts

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[1] This relation usually breaks down a few hundred milliseconds before the catch is taken, when the hands start to move toward the ball. Fielders follow one strategy to get to within reach of the ball and another to move their hands to the place where they will make the catch. This article is concerned only with the former strategy—how the fielder gets to the place where the ball is within arm's reach.

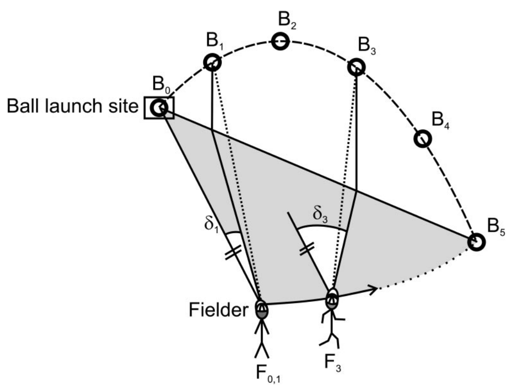

Figure 1. δ is the horizontal angle through which the fielder rotates to fixate the ball. F indicates the fielder's position, and B indicates the ball's position.

to move. δ_1 is the horizontal angle between the direction from the fielder to the initial position of the ball and the direction from the fielder to the vertical projection of the ball to the ground. By the time the ball reaches B_3, the fielder has moved to F_3. δ_3 is the horizontal angle between a line from the fielder parallel to the original direction from the fielder at F_0 to the ball at B_0 and a line from the fielder to the vertical projection of the ball at B_3 to the ground. Thus, δ_t is the time integral of the fielder's rotation by time *t*. In our analysis of the fielder's running paths, we refer to the initial direction of rotation (whether clockwise or anticlockwise) as positive. If δ_t is positive, the fielder is laterally behind the ball; if it is zero, he or she is in line with it; if it is negative, he or she is ahead of it. $d\delta/dt$ is the instantaneous speed at which the fielder's tracking system is rotating to maintain fixation on the ball, and its sign is the direction—if positive, rotation is in the same direction as the initial movement; if negative, it is in the opposite direction.

Figure 2 shows typical patterns of δ and $d\delta/dt$ during a catch for various relations between the fielder's lateral velocity (i.e., in a direction at right angles to the initial direction from fielder to ball) and the ball's. As an example (illustrated in bird's eye view at the top of the figure), we have considered a ball projected at 30 m from a fielder, which would land 10 m to the right of the fielder's initial position 3 s later. We assume that the fielder is stationary, watching the ball, for 0.5 s before starting to run. During this time, the ball will get laterally ahead of the fielder, and δ will increase. If, once the fielder starts moving, his or her lateral velocity is less than the ball's, δ and $d\delta/dt$ will increase throughout the flight as the fielder falls farther behind the ball. Figure 2e shows how they change when the fielder's (constant) lateral velocity is sufficiently less than the ball's that it will fall just beyond the reach of the fielder's outstretched hand. If the fielder's lateral velocity exceeds the ball's, δ will become negative as the fielder gets ahead of the ball. Figure 2a shows δ and $d\delta/dt$ for a fielder whose (constant) lateral velocity is sufficiently greater than the ball's that it is just out of arm's reach behind him or her as it falls.

If the fielder is to intercept the ball, his or her lateral velocity averaged across the flight should be roughly equal to the ball's (terminal arm movements can compensate for a minor mismatch). Figures 2b–2d show the pattern of δ and $d\delta/dt$ that will accompany some representative examples in which the fielder arrives at the interception point at the same time as the ball. If the fielder were to accelerate past the ball and then slow down as he or she approached the plane of the ball's flight (i.e., Jacobs et al.'s, 1996, strategy) the pattern would look like Figure 2b if the acceleration and deceleration were constant and symmetrical. If the fielder were to accelerate at a constant rate until he or she achieved lateral alignment with the ball and then slow down and run at the same speed as the ball (i.e., Chapman's, 1968, strategy), it would look like Figure 2c. If the fielder accelerated continuously through the flight at a constant rate such that he or she arrived at the interception point at the same time as the ball, δ would increase at an approximately constant rate throughout the flight (Figure 2d). This pattern may seem counterintuitive. Because the lateral distance between fielder and ball decreases once the fielder starts to run, one might expect $d\delta/dt$ to be negative toward the end of the flight. However, as the ball is getting nearer to the fielder in depth faster than the lateral distance between them is reducing, δ increases throughout the flight despite the fact that the fielder is catching up with the ball laterally and will intercept it.

The lateral relation between fielder and ball is different for each of the successful strategies in Figures 2b–2d. What they have in common is that δ does not accelerate—$d\delta/dt$ is constant for the latter part of the flight. In contrast, if the fielder is going to miss the ball because he or she is running either too slowly or too fast, δ accelerates.

For efficient interception, fielders must run so that α increases (see McLeod & Dienes, 1996). But there is no lateral strategy that *must* be adopted. Any of the strategies in Figures 2b, 2c, or 2d will help fielders intercept the ball, as they will move them toward the ball's flight plane at a speed that brings them to the interception point at the same time as the ball. Different strategies may well be adopted for different catches. If there is plenty of time to make the catch, fielders might try to get ahead of the ball and then slow down as they approach the interception point, possibly reaching the plane of the ball's flight before they take the catch. But when they have to run faster to make the catch, they might approach the plane of the ball's flight from the side, only reaching the plane at the moment that they take the catch. We have analyzed lateral movement in two different catching tasks. In the first the catches were easy, and the fielders were under little time pressure to take the catch. In the second the catches were harder, and the fielders had to move as quickly as they could to take some of them.

An alternative to the OAC approach to interception is the linear optic trajectory (LOT) theory (McBeath, Shaffer, & Kaiser, 1995). The claim is that the fielder achieves interception by running so that an optic trajectory defined by the ratio of vertical and horizontal angles from fielder to ball remains linear. Thus, unlike in OAC theory, the fielder does not actively control the angles between himself or herself and the ball. He or she controls the optic trajectory, and, in consequence, the vertical and horizontal angles change. We describe the differences between LOT and GOAC theory in detail later, but here we summarize why an alternative to LOT theory is needed and what form it needs to take.

First, the data cited in favor of LOT theory consistently deviate from the predictions of that theory (McLeod et al., 2001; McLeod, Reed, & Dienes, 2002). If the fielder maintains a linear optic trajectory, then the horizontal angle between the fielder and the ball will increase in constant proportion to the vertical angle. Although the vertical angle between fielder and ball rises during

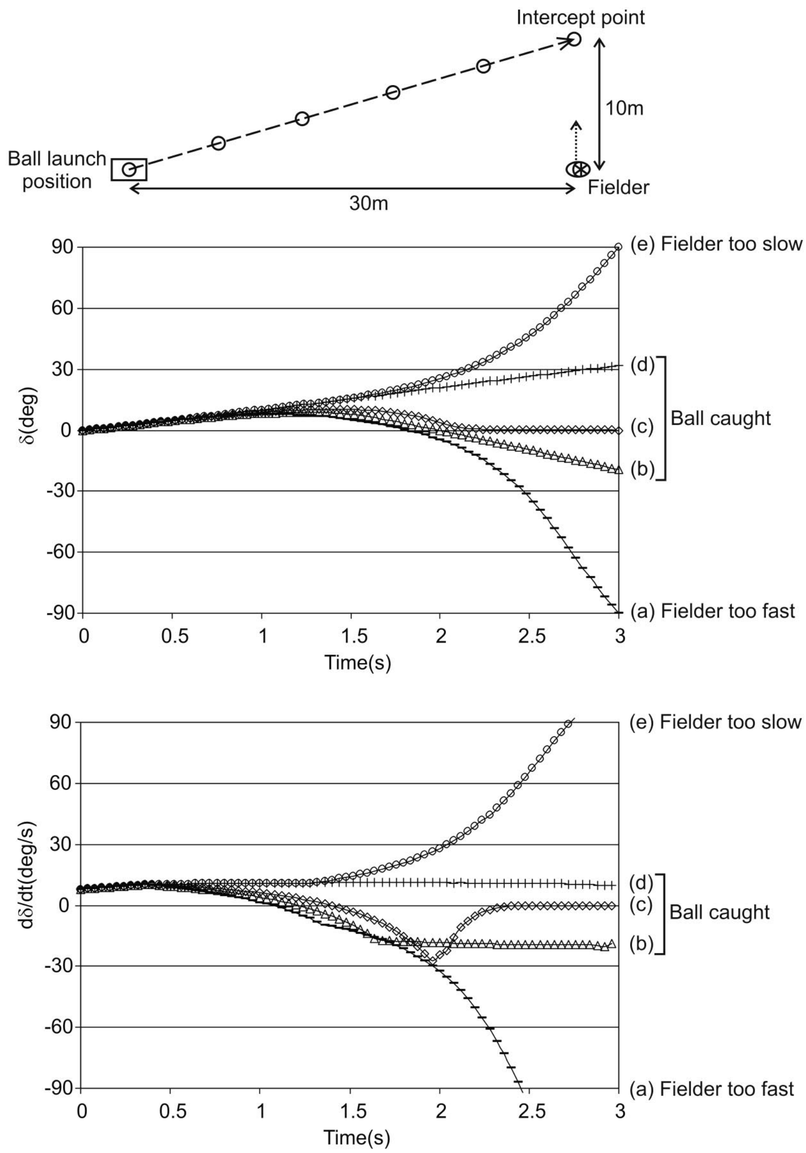

Figure 2. How δ and *d*δ/*dt* change as the fielder runs to catch a ball that will fall at the intercept point. (a) The fielder runs too fast and overshoots the interception point. (e) The fielder runs too slowly and fails to reach the interception point in time. (b), (c), and (d) The fielder follows different running patterns but in each case reaches the interception point at the same time as the ball.

all catches and the horizontal angle rises in many catches, they do not always do so in constant proportion. This suggests that a theory in which control of changes of the vertical and horizontal angles are uncoupled could give a better fit to the data than one in which they are linked. Second, LOT theory offers no natural explanation of how fielders move in the appropriate direction to catch a ball coming directly toward them. Because the horizontal angle between fielder and ball remains at zero throughout such a catch, changes in vertical and horizontal angle cannot be matched. Again, allowing independent strategies for controlling change of vertical and horizontal angles might lead to a more parsimonious theory (i.e., one that explains how balls are caught whether they are going directly toward the fielder or to one side). Third, because LOT theory requires changes in vertical and horizontal angle to be coupled and because it is known empirically that the vertical angle always increases throughout the flight, the horizontal angle must always increase throughout the fight. That is, the fielder must approach the plane of the ball's flight from the side. There is no possibility of the fielder moving into the flight plane before the catch is taken no matter how much time there is to take the catch or how close the fielder is initially to the plane of the ball's flight. A theory that decouples control of vertical and horizontal angles would allow for different strategies for different catches. For example, fielders might move into the plane of the ball's flight before they take a catch when they have plenty of time to get there but not when they can only just get there in time.

In this study, we show that GOAC theory, which decouples the control of the horizontal and vertical angles between fielder and ball, delivers on all three promises. It offers a better fit to the empirical data than LOT theory, it offers a natural explanation of how people catch balls headed directly toward them as well as to the side, and it explains why people use different strategies to catch balls on different trajectories, sometimes reaching the plane of the ball's flight before taking the catch and sometimes not. It also offers an account of individual differences in catching style.

Experiment 1

Method

Subjects. The subjects were 5 male cricketers ranging in age from 24 to 52 years. They were competent but not highly skilled fielders.

The catching task. Tennis balls were projected with a launch angle of 63° above 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 four positions. These represented various combinations of distance laterally and in depth that they had to move to catch the ball—3 m to the left and 4 m back, 3 m to the right and 2 m back, 4 m to the right and 4 m forward, and 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. This task was undemanding for experienced cricketers. The fielders had enough time to cover a relatively short distance, and all fielders caught all balls. All fielders took all catches two handed, the natural way for a cricketer to catch the ball.

Measuring the fielder's position and the ball's trajectory. The position of the fielder was recorded on a video camera mounted 14.5 m above the ground and 5.9 m behind the ball projection machine. The position of a fielder standing at a matrix of points 2 m apart laterally and in depth covering the area in which the fielders ran was recorded. We applied a curve-fitting program to these known positions to generate a polynomial mapping function to invert the trapezoidal representation on the video film back to positions on the ground. We determined the fielders' positions at 40-ms intervals by applying this mapping function to their positions on the video image.

The position of the ball throughout each flight was computed using the method described by Brancazio (1985) and Dienes and McLeod (1993). The duration of the flight and the distance the ball traveled were taken from the film. These figures, combined with an estimate of the drag on a tennis ball at the velocities achieved in the experiment (taken from Daish, 1972), were used to get a best fit for initial velocity. These were used to calculate the position of the ball throughout the flight. The positions of ball and fielder were then used to calculate δ at 40-ms intervals.

This experiment is a reanalysis of Experiment 2 of McLeod et al. (2001) to determine the fielders' behavior in terms of δ.[2] Details of the fielders' running paths and the values of α experienced by the fielders are given in the *Results* section of that article. All fielders for all catches experienced α increasing at a decreasing rate as they ran. Fuller details of the method used for computing the fielder's position from the video film and for determining the accuracy of the calculation of the ball's position are given in the *Method* section of that article.

Results and Discussion

Figure 3 shows how δ changed from the time the ball appeared to the time at which fielders made a two-handed movement toward the ball (typically about 0.5 s before they caught the ball). The data are averaged across the 40 catches for each fielder, as they produced similar patterns from each starting position. δ initially increased (see Figure 1). When the fielders started to run, the

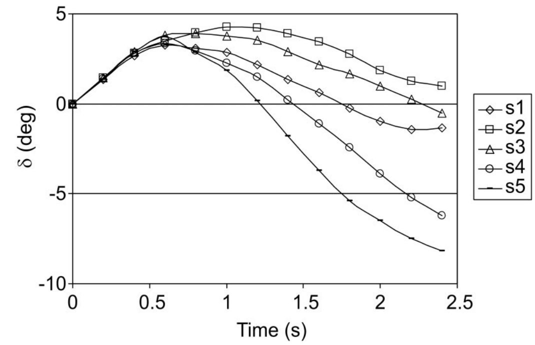

Figure 3. How δ changed in Experiment 1. Individual data are given for 5 fielders (s1 through s5 = Subjects 1 through 5).

increase in δ slowed and then followed one of two patterns. For 3 of the fielders, δ returned to zero. For the other 2, δ became increasingly negative. Although there was some trial-to-trial variability, the consistency of these strategies for each fielder and the consistency of the differences between them are shown in Figure 4. This shows the value of δ at the time that a hand movement was made toward the ball for all 40 catches for each of the 5 fielders. Three of the subjects (the upper three in Figure 3) showed symmetrical distributions centered on zero. The other 2 showed a negative terminal δ for most catches.

The fielders who reduced δ to zero accelerated until they achieved lateral alignment with the ball and then matched their lateral speed to that of the ball so that there was no further lateral movement of the ball relative to themselves. This is the strategy suggested by Chapman (1968). Negative δ occurs when fielders accelerate until they get laterally ahead of the ball and then slow down as they approach the plane of the ball's flight (Figure 2b). This was the strategy adopted by the baseball fielder analyzed by Jacobs et al. (1996).[3]

Analysis of the speed of the fielders as they took the catches supports the idea that fielders were using two different strategies. We measured the lateral velocity of the fielder (i.e., in a direction at right angles to the direction from fielder to ball) in the last 200 ms before they took the catch and compared this with the average throughout the catch. The average lateral speed throughout all catches across the 5 fielders was 1.23 ms^{-1}. This did not differ significantly among fielders. The terminal speed for Fielders 1–3 averaged 0.99 ms^{-1}, and for Fielders 4 and 5 it averaged 0.49 ms^{-1}. The terminal velocity of Fielders 4 and 5 was reliably less than that of Fielders 1–3 ($p < .05$ for all comparisons, Mann–Whitney U test). As suggested by the analysis of δ, Fielders 4 and 5 ran faster initially, getting ahead of the ball, and then slowed down as they reached the plane of the ball's flight, whereas

[2] McLeod et al. (2001) analyzed the fielders' movements in terms of the horizontal angle β defined by the LOT theory of catching (McBeath et al., 1995). We discuss the difference between β and δ as measures of the horizontal relation between fielder and ball in detail later in the article.

[3] Figure 2 in Jacobs et al. (1996) shows the ball moving an impossible distance and the fielder running at an improbable speed. The scales in their Figures 2A and 2B should be in feet and feet per second, not meters and meters per second (T. Jacobs, personal communication, 2002).

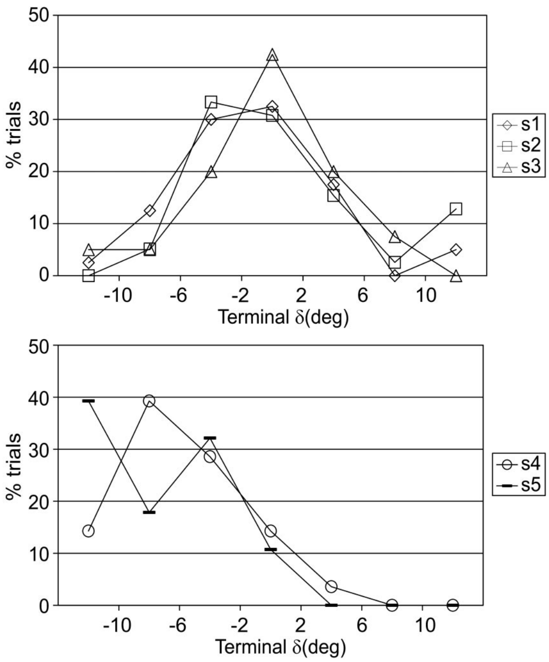

Figure 4. The terminal value of δ for each catch for each fielder in Experiment 1 (s1 through s5 = Subjects 1 through 5).

Fielders 1–3 were closer to matching the lateral speed of the ball as they took the catch.

One might argue that the fielders learned where the ball would fall, ran to that position, and waited for the ball. If the fielders were doing this, their terminal speed would become less as they learned the task. We tested this by comparing the fielders' running speed in the 200 ms before they caught the ball in the first 12 and the last 12 of their 40 catches. The mean speed across the 5 subjects was 1.45 ms^{-1} (SD = 0.73) for the first 12 catches and 1.62 ms^{-1} (SD = 0.84) for the last 12. The difference between the first and last 12 catches was not statistically significant for any individual fielder. Fielders were not learning where the ball would fall, running there, and waiting for it.

Experiment 2

The catches in Experiment 1 were easy. In Experiment 2, the fielders had less time to take the catch. The aim of the analysis was to see how δ changed as the fielders ran to take these harder catches.

Method

Subjects. These were 5 male cricket players and 1 female soccer goalkeeper. Their ages ranged from 18 to 51 years. All were of no more than enthusiastic amateur skill level at ball games.

Catching task. Fifty tennis balls were projected to each fielder from a height of 14.75 m above the ground. The fielders stood at ground level, starting 13.5 m horizontally from the ball's projection point. The balls were projected in a random direction and with a range of initial 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 that the subjects could just catch running as fast as they could, to ones that fell out of reach. Thus, most catches were considerably harder than those in Experiment 1. The positions of the fielder and ball were measured in the same way as in Experiment 1, and from these δ was computed at 40-ms intervals. All successful catches (n = 165) were analyzed.

This experiment is a reanalysis of Experiment 1 of McLeod et al. (2001) to examine fielders' behavior in terms of δ (see Footnote 2). Further details of the method, the fielders' running paths, and the values of α they experienced can be found in that article. All fielders for all catches experienced α increasing at a decreasing rate as they ran.

Results and Discussion

The upper part of Figure 5 shows how δ changed throughout the catch. The functions end at the time that the fielder initiated a two-handed movement toward the ball, typically about 0.5 s before the catch was taken. The data are grouped according to how far the fielders ran laterally to make the catch, independent of how far they ran in depth. The lower function is averaged across 9 catches for which the fielder had to move less than 2.1 m laterally, the middle function is averaged across 136 catches for which the fielder had to move between 2.1 and 4.2 m, and the upper function is averaged across 20 catches for which the fielder had to move more than 4.2 m.

When the fielder made a relatively small lateral movement, δ remained at a constant value close to zero. This is similar to the pattern produced by 3 of the fielders for the catches in Experiment 1. If they had to run further, δ increased as they ran, and the further they had to run the more δ increased. We performed a linear regression of δ against time between 0.4 s (by which time fielders had usually started to run) and 1.32 s (when they typically started to make a hand movement toward the ball). Figure 6 shows the slopes of the linear regressions for the 165 catches. There was a continuous distribution of slopes from -11 deg/s^{-1} to $+21$ deg/s^{-1}. The median value of r^2 for the linear component of the regression across all flights was .91. This suggests that fielders tried to keep the rate of change of δ constant as they ran. We test this interpretation in the simulation described later.

The lower part of Figure 5 shows the fielders' lateral velocity grouped across catches in the same way as in the upper part of Figure 5. One can see that the fielders' lateral movement was initially similar in all cases, with an acceleration in the correct direction. Then the fielders who were going to move less than 2.1 m laterally decelerated gently for the rest of the catch, those running 2.1–4.2 m continued to accelerate gently, and those running more than 4.2 m accelerated more rapidly. In the upper part of the figure, one can see what the fielders achieved by these running patterns. In each case, the initial rate of increase of δ decreased. The result of the fielder's running was to bring the increase in δ under control and prevent it accelerating, as it would do if the fielder's speed was inappropriate for achieving interception (see Figures 2a and 2e).

One might argue that fielders do not follow a continuous servo strategy based on the information they get from watching the ball as they run (as both the GOAC and LOT theories assume) but make a prediction of where the ball will fall from their initial observation of the trajectory and run to the interception point. The data in the lower part of Figure 5 make such a theory implausible. The fielders were always moving when they took the catch. If they

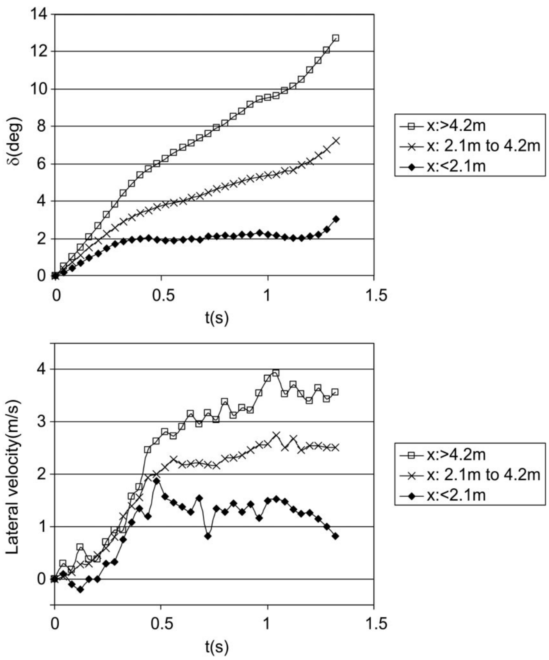

Figure 5. Upper panel: δ as a function of the lateral distance (x) that the fielder ran. Lower panel: The fielders' lateral velocity as a function of the lateral distance (x) run.

knew where the ball was going to fall, they would presumably go there and wait for it.

Summary

The experiments show that the fielders used all three interception strategies illustrated in Figures 2b–2d. What these strategies have in common is that the fielder did not allow δ to accelerate. On different ball trajectories, this is achieved by keeping $d\delta/dt$ zero or constant with a negative or positive value. There were also systematic differences in strategy among different fielders. In contrast, in all the catches reported in both experiments, α increased at a decreasing rate. So, in contrast to the claim of LOT theory, the vertical and horizontal angles between fielder and ball do not change in the same way during the course of the catches or in the same way for different fielders.

General Discussion

Using the Rate of Horizontal Rotation to Aid Interception

A direct cue to fielders that they are not in the right place to take the catch is that there is a horizontal component to the rotation of the tracking system as they follow the ball. It is unlikely that δ, the angle through which they have rotated, would be available to the fielders, but they would know whether they were rotating. So the rate of rotation, $d\delta/dt$, is likely to contribute to the fielder's interception strategy rather than δ.

Any strategy that uses the rate of horizontal rotation of the tracking system as a cue will move the fielder toward the plane of the ball's flight throughout the flight and so increase the range of trajectories that can be intercepted compared with the pure OAC strategy, which uses $d\alpha/dt$ alone. The lower part of Figure 2 shows the relation between $d\delta/dt$ and the lateral velocities of fielder and ball. If the fielder's lateral velocity is less than the ball's, $d\delta/dt$ becomes increasingly positive throughout the catch (as shown in Figure 2e); if the fielder's lateral velocity is greater than the ball's, $d\delta/dt$ becomes increasingly negative throughout the catch (as shown in Figure 2a). So a servo that took the rate of horizontal rotation of the tracking system as its input and produced lateral acceleration of the fielder as its output could aid interception by moving the fielder's lateral velocity toward that of the ball. In general, if the fielder is moving laterally more slowly than the ball, $d\delta/dt$ will be positive, so the fielder will accelerate; if he or she is moving faster than the ball, $d\delta$/dt will be negative, so he or she will decelerate. Moving into the plane of the ball's flight does not guarantee interception, as the fielder may reach it at a position where the ball is out of reach overhead. A strategy based on α is also required to make sure that the fielder moves to the place on the ball's flight plane where it is at catching height.

The GOAC Theory of Interception

This is a development of the proposal originally made by Chapman (1968) and elaborated by Tresilian (1995) that interception is achieved by a combination of control of the rate of change of the vertical rotation of gaze to the ball and the use of a cue, based on the rate of change of the horizontal rotation of gaze, that moves the fielder toward the ball's flight plane throughout the catch.

GOAC theory starts from the observation, self-evident to anyone who has ever caught a ball (and now with empirical backing; Oudejans et al., 1999), that fielders look at the ball as they move to take a catch. It is based on the assumption that the signals generated by tracking the ball are the basis of the fielder's interception strategy. Vertical rotation of the tracking system generates a signal based on $d\alpha/dt$. This is the input to a servo mechanism that moves the fielder so that α increases at a decreasing rate. Horizontal rotation of the tracking system produces a signal based on $d\delta/dt$. This is the input to a servo mechanism that moves the fielder so that $d\delta/dt$ is constant (or zero). (If the ball comes directly toward the fielder, $d\delta/dt$ is zero throughout the flight, so the fielder will not move sideways.)

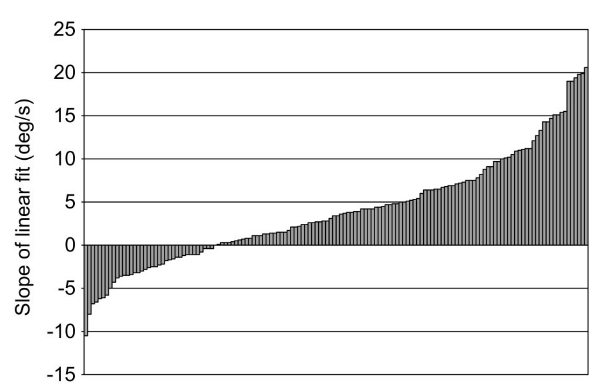

Figure 6. The slope of the linear regression of δ against time between 0.40 s and 1.32 s for the individual catches in Experiment 2.

The way that these two constraints control the path taken by the fielder is shown in Figure 7. The fielder should run forward and to the right to catch the ball. The upper part of the figure shows how the fielder moves so that α increases at a decreasing rate. (Empirically, the decreasing rate is such that tanα increases at a constant rate.) The constraint that α should increase to a specific value at the next time interval requires the fielder to move to somewhere on a circle centered on the vertical projection to the ground from the position that the ball will reach at that time. The circle is the locus of points from which the angle of elevation from fielder to ball has the required value of α. A segment of this circle is shown for the time interval that will end with the ball at position B_4. The fielder at position F_3 must reach this circle by the time the ball reaches B_4. The second constraint, that δ should change at a constant rate, requires the fielder to be somewhere on a line from which δ will have the correct value given the position of the ball at the end of the time interval. This is shown in the lower part of the figure, a bird's eye view of fielder and ball, for the time interval that will end with the ball in position B_4. The fielder at position F_3 must reach this line by the time the ball gets to B_4.

To satisfy both constraints, the fielder moves to the position where the line and circle intersect. Thus, the fielder does not explicitly choose a direction or a speed at which to run. These emerge as a consequence of moving in a way that satisfies the constraints on the rates of change of α and δ. This view of the fielder's strategy as local constraint satisfaction rather than a calculation of where the ball will fall accords with the subjective sensation of running to catch a ball. One does not know where the ball will land, but one does know that one will be able to intercept the ball (or not). This reflects the knowledge that one has been able to move to a position where the constraints on $d\alpha/dt$ and $d\delta/dt$ have been satisfied (or not).

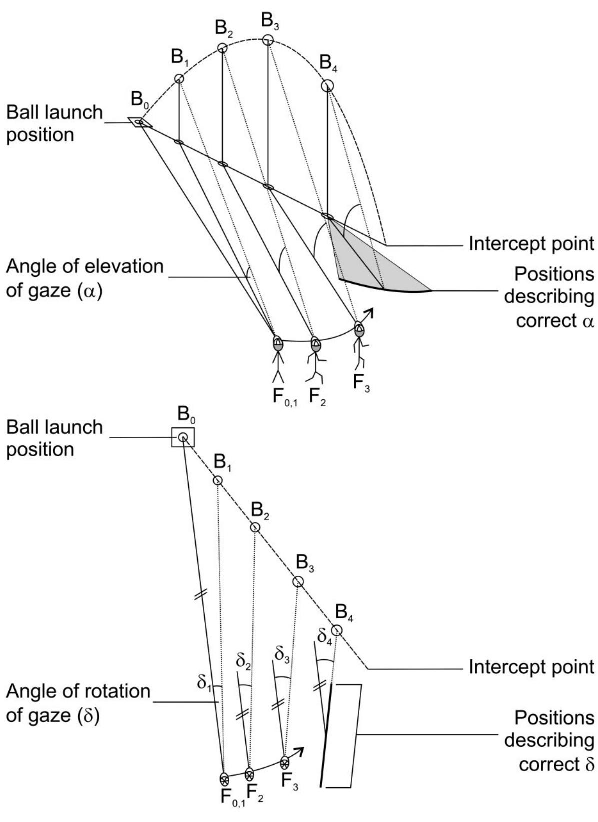

Figure 7. Upper panel: The arc that the fielder at F_3 must reach by the time the ball has reached B_4 to satisfy the constraint that α increases at a specific decreasing rate. Lower panel: The line that the fielder at F_3 must reach by the time the ball has reached B_4 to satisfy the constraint that δ changes at a constant rate. F indicates the fielder's position, and B indicates the ball's position.

The LOT Theory of Catching

The main alternative to the OAC approach to interception has been LOT theory, proposed by McBeath et al. (1995; McBeath, Shaffer, & Kaiser, 1996; Shaffer & McBeath, 2002; Shaffer, McBeath, Roy, & Krauchunas, 2003). According to this theory, the fielder has access to a projection surface on which the image of the ball follows a trajectory with a direction defined by the ratio α/β. α is the angle of elevation of gaze, as in GOAC theory; β 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 (see Figure 8). The claim is that if the fielder runs in a way that keeps this trajectory linear (i.e., the ratio α/β remains constant[4]), he or she will intercept the ball—hence, linear optic trajectory theory.

The Relation Between α and β

LOT theory analyzes the lateral relation between ball and fielder in terms of β; GOAC theory analyzes it in terms of δ. β can be divided into two parts by a line through the fielder parallel to the initial orientation from fielder to ball. δ is a subpart of β (see Figure 9). The remaining part of β we refer to as β_1. $\beta = \delta + \beta_1$.

The observation that led McBeath and his colleagues to propose LOT theory was that when fielders ran to catch the ball, β increased in roughly equal proportion to α. An increase in β as fielders run is also consistent with one of the lateral control strategies of GOAC theory. If the fielder approaches the ball's flight plane from the side, δ will increase throughout the catch (see Figure 2d). Figure 10 shows that as the catch progresses, β_1 will also increase as a geometric consequence of the fielder getting closer to the plane of the ball's flight. Because δ and β_1 are increasing, there will be an increase in β throughout the flight. Thus, we would expect the observation that β increases as the fielder runs if the fielder is trying to control lateral movement of the ball relative to himself or herself, as suggested by GOAC theory.

The close relation between β and δ may make the two theories seem similar, simply disagreeing over which angle is the more appropriate way to represent the lateral relation between ball and fielder. In fact, GOAC and LOT are fundamentally different theories of how interception is achieved. According to GOAC theory, the fielder tracks the ball, producing signals based on $d\alpha/dt$ and $d\delta/dt$. These act as the input to servo mechanisms that control the movement of the fielder, who tries to achieve a particular pattern of change for the two angles. The fielder achieves interception

[4] And α increases (see Dannemiller, Babler, & Babler, 1996).

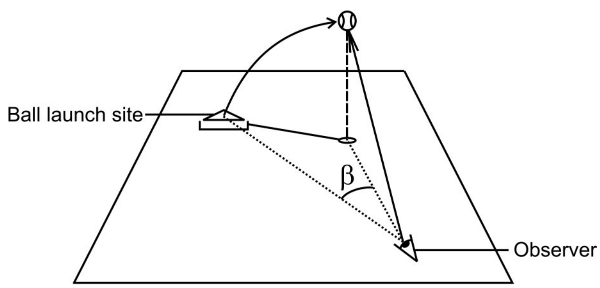

Figure 8. The lateral angle β as defined by linear optic trajectory theory (McBeath et al., 1995).

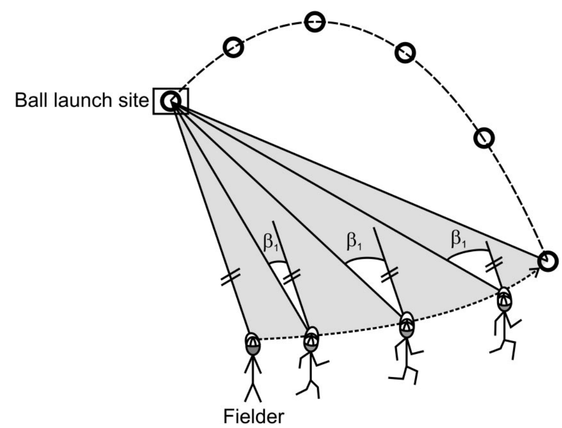

Figure 10. The increase in β_1 that occurs if the fielder approaches the ball's flight path from the side.

through active control of the rate of change of vertical and horizontal angles between fielder and ball. According to LOT theory, in contrast, the fielder achieves interception by running so that the optic trajectory is linear. There is no active control of the vertical and lateral angle between fielder and ball. They are controlled indirectly as a consequence of keeping the optic trajectory linear.

A Comparison of LOT and GOAC Theories of Interception

To compare these two theories of interception, we calculated the position of two simulated fielders watching the flight of balls that had been caught by real fielders in Experiment 2. One fielder moved along the path predicted by GOAC theory, and the other moved along the path predicted by LOT theory. We then compared these paths with those of the real fielders.

The simulated fielders were moved to the same positions as the real fielder for the first 600 ms after the ball appeared in order to give them the same initial experience of each ball flight as the real fielder. After this they were moved at 40-ms intervals to the position predicted by the two theories. The simulated fielder following GOAC theory was first moved to a position such that α increased at the average decreasing rate experienced by the real fielder over the first 600 ms after ball launch. (The decreasing rate was chosen by keeping $d(\tan\alpha)/dt$ constant at its average value over the first 600 ms.) This placed the fielder somewhere on a circle centered on the vertical projection of the ball to the ground (as in the upper part of Figure 7). The fielder's position on the circle was selected such that δ changed at the average rate experienced by the real fielder between 0.48 s and 0.68 s. The simulated fielder following LOT theory was first moved so that he experienced the value of α experienced by the real fielder. As with the GOAC fielder, this placed him somewhere on a circle centered on the vertical projection of the ball to the ground. The position on the circle was selected such the change in β for that step matched the change in α. That is, he moved so that the ratio α/β remained constant throughout the catch. The distance the simulated fielder could move in each time step was limited to a maximum speed of 7 ms^{-1} and a maximum acceleration of 4 ms^{-2}. These approximate the limits of real fielders observed in the experiments. The eyeheight of the simulated fielder was 170 cm.

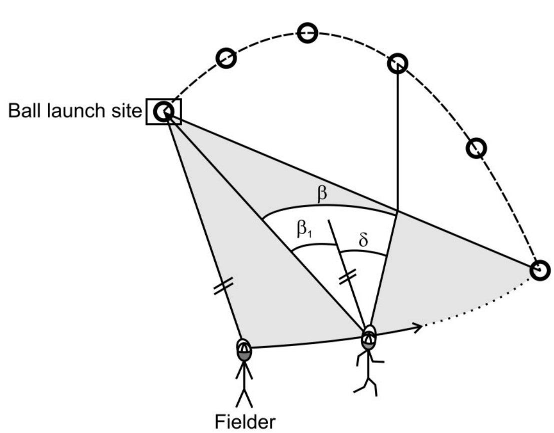

Figure 9. The relation between β in linear optic trajectory theory and δ in generalized optic acceleration cancellation theory.

Figure 11 shows the paths of the simulated and real fielders for a representative set of catches where the fielders ran in a range of directions. The arrow marks the position that the real fielder had reached at the point where the simulated fielders took over. One can see that both models give a good approximation of the paths of the real fielders. We compared the performance of the two models (i.e., how close the simulated fielder was to the path of the real fielder watching the same ball trajectory) between 600 ms after the ball was launched and the time at which the real fielder made a synchronous movement of the hands to catch the ball (the point at which we assume that other mechanisms take control of interceptive behavior). The mean difference between the position of the simulated fielder following the constraints of GOAC theory and real fielders across the 165 catches was 19.0 cm. This was not reliably different from the positional error in estimating the position of the fielder (15.9 cm; $z = -0.47$, $p = .64$). (The method of measuring the error in our estimates of the fielder's position was to film a fielder following a known path and then measure the deviation between that path on the ground and the estimate of it calculated from the video. The main source of error is the vertical movement of the fielder's head as he or she runs, which appears partly as a lateral displacement of the fielder in the video. The method is described in detail in McLeod et al., 2001.) The mean error of the fielder following LOT theory was 22.4 cm. This was reliably worse than the fielder following GOAC theory, $t(164) =$

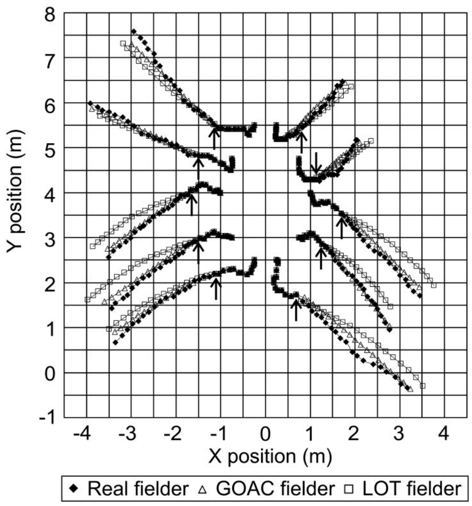

Figure 11. The paths followed by simulated and real fielders, viewed from above, for 10 catches for which the fielder ran in different directions. The real fielder always started at (0, 4). We have spread the running paths out from this point to make them easier to see. They end at the point where the fielder made a two-handed movement to catch the ball. GOAC = generalized optic acceleration cancellation; LOT = linear optic trajectory.

3.34, $p < .001$. We also compared how far the simulated fielder was from the real fielder at the time that the real fielder made a two-handed movement toward the ball. The terminal error of the simulated fielder following GOAC theory was 24.4 cm (SD = 15.5); the terminal error of the simulated fielder following LOT theory was 34.3 cm (SD = 19.7). The terminal error of the LOT prediction was reliably greater than that of the GOAC prediction, $t(164) = 6.6$, $p < .001$.

The fielder following GOAC theory was consistently closer to the path of the real fielder than the fielder following LOT theory. However, it is clear that the path of the fielder following LOT theory was often a reasonable approximation to the path of the real fielder. In our view, this is not because the fielder was attempting to keep the optic trajectory linear. The fielder's strategy has two components. The first is to allow α to increase. The second is to prevent δ accelerating. If the fielder has to run quite fast to catch the ball, this is achieved by allowing a constant rate of increase in δ. The consequence is that the fielder approaches the ball's flight plane from the side and β increases. Thus, α and β will both increase, and the ratio α/β may remain roughly constant as the fielder runs. This result is a geometric consequence of the fielder following the GOAC strategy, not a consequence of trying to keep the optic trajectory linear.

Different Strategies for Different Catches

In the catching task reported by McLeod et al. (2001; the task reanalyzed as Experiment 1 in this article), α increased at a decreasing rate throughout every catch. Thus, according to LOT theory, β must increase at a decreasing rate because the fielder runs in a way that keeps the ratio α/β constant. But this did not happen. Initially, β always increased (as it must do before the fielder starts to move), but then for some catches it decreased, for some it remained roughly constant, and for others it increased, sometimes slowly, sometimes more rapidly. If one analyzes the fielders' strategy in terms of δ, this can be understood. For those catches for which the fielder moves laterally ahead of the ball (those for which δ is negative toward the end of the flight), β will decrease. For those catches for which the fielder moves in lateral alignment with the ball (those for which δ is zero toward the end of the flight), β will increase slowly because of the increase in β_1 as the fielder approaches the plane of the ball's flight. For those catches for which the fielder catches up laterally with the ball throughout the flight, allowing δ to increase, β will increase more rapidly as both β_1 and δ will be increasing as the fielder approaches the ball. The inconsistency of β occurs because fielders use different strategies for the control of lateral movement depending on the lateral speed of the ball relative to themselves, how long they wait before starting to run, and, possibly, their personal preferences. LOT theory, in which α and β are always linked, cannot explain this. GOAC theory, in which changes in α and δ are controlled independently, can.

Although fielders in real ball games are often moving as they take a catch, they sometimes go to the place where the ball will fall and wait for it. This observation has been used as evidence against LOT theory (Chodosh, Lifson & Tabin, 1995), as LOT theory predicts that fielders will always run through the point where the catch is taken at the moment the ball arrives. GOAC theory has an explanation for why fielders will sometimes be moving and sometimes be stationary when they take a catch. Use of the α strategy will typically lead to the fielder moving through the point where the catch is taken. But there is no such constraint on the δ strategy. If the fielder has time, he or she can move into the plane of the ball's flight and stop. Thus, if a fielder is close to the correct distance in depth to take the catch but has to move laterally, then the strategy may take the fielder to the place where the catch can be taken before the ball arrives, and the fielder will be stationary when the catch is taken.

Summary

The GOAC theory of catching proposes that the path taken by a fielder running to catch the ball is determined by the attempt to satisfy two independent constraints. The first is to keep the angle of elevation of gaze as the ball is tracked increasing at a decreasing rate; the second is to control the rate of horizontal rotation necessary to maintain fixation on the ball. Depending on the lateral velocity of the ball relative to the fielder, the latter may be done by keeping the rate of rotation zero or constant at a negative or positive value. If the fielder can run fast enough to satisfy these constraints, he or she will catch the ball.

GOAC theory provides a good fit to empirical data on the paths that people follow when running to catch a ball. It explains how people catch balls headed directly toward them as well as to the side. It also explains why people use different strategies to catch balls on different trajectories, reaching the plane of the ball's flight before taking the catch if they do not have to move quickly sideways to catch the ball but only reaching the plane of the ball's flight as they take the catch if they have to move fast laterally to take the catch. The different strategies for controlling lateral movement offer a basis for individual differences in catching style.

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