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Optical Trajectories and the Informational Basis of Fly Ball Catching

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D. M. Shaffer and M. K. McBeath (2002) plotted the optical trajectories of uncatchable fly balls and concluded that linear optical trajectory is the informational basis of the actions taken to catch these balls. P. McLeod, N. Reed, and Z. Dienes (2002) replotted these trajectories in terms of changes in the tangent of optical angle over time and concluded that optical acceleration is the informational basis of fielder actions. Neither of these conclusions is warranted, however, because the optical trajectories of even uncatchable balls confound the information that is the basis of fielder action with the effects of those same actions on these trajectories. To determine the informational basis of fielder action, it is necessary to do the control-theory-based Test for the Controlled Variable, in which the informational basis of catching is found by looking for features of optical trajectories that are protected from experimentally or naturally applied disturbances.

Shaffer and McBeath (2002) tried to determine the informational basis of fly ball catching by observing the optical trajectories of uncatchable fly balls as seen by fielders running to catch these balls. They reasoned that the information fielders use to catch fly balls should be apparent in the optical trajectories of uncatchable balls in terms of how long a potential cue, such as spatial linearity, is maintained relative to other cues, such as optical acceleration. Because the linearity of optical trajectory was maintained longer than the constancy of optical acceleration, Shaffer and McBeath concluded that the information fielders use as the basis of action is the linear optical trajectory (LOT) of the balls, which is consistent with LOT theory (McBeath, Shaffer, & Kaiser, 1995).

In reviewing the results of Shaffer and McBeath (2002), McLeod, Reed, and Dienes (2002) noted that there is a consistent and pronounced downward curvature in the trajectories of balls that go over the fielder's head, which incorrectly indicates that the ball is going to fall short. McLeod et al. replotted these trajectories in terms of the tangent of the vertical optical angle of the ball ($\tan\alpha$) over time and found that $\tan\alpha$ increases at an accelerating rate, which correctly indicates that the ball is going to go over the fielder's head. McLeod et al. concluded, therefore, that acceleration of $\tan\alpha$ is the information that fielders use as the basis of their actions, which is consistent with optical acceleration cancellation (OAC) theory (Dienes & McLeod, 1993; Michaels & Oudejans, 1992).

The Shape of Optical Trajectories

Although Shaffer and McBeath (2002) and McLeod et al. (2002) disagreed about the informational basis of fly ball catching, they agreed that clues to what this information is can be found in the optical trajectories seen by fielders when they try to catch uncatchable fly balls. Indeed, in their reply to McLeod et al. (2002), Shaffer, McBeath, Roy, and Krauchunas (2003) pointed to the linearity of optical trajectories during all but the last moments of attempted catches as evidence that this information provides a viable basis for catching fly balls. This argument shows that the shape of optical trajectories remains the basic evidence in the debate about the informational basis of catching.

One argument for using the trajectories of uncatchable fly balls to determine the informational basis of catching is that the information in these trajectories is more readily apparent because it is not entirely nulled by the fielder's own actions (McLeod et al., 2002). However, this argument ignores the fact that the feedback effects of fielder actions on the trajectories of even uncatchable fly balls are still present, and they are strong. The shapes of the optical trajectories that are observed when fielders run to catch even uncatchable fly balls depend as much on the fielders' actions relative to the balls as they do on each ball's actual trajectory. Therefore, the information that is the basis of a fielder's actions cannot be seen in the shape of these trajectories, because this information is confounded with the effects of those same actions on the trajectories.

Looks Can Be Deceiving

The problem of determining the informational basis of catching by looking at the optical trajectories of uncatchable fly balls can be illustrated using a computer model of a fielder trying to catch such balls. Several such models have been developed (e.g., Marken, 2001; Tresilian, 1995). These are closed-loop control models, which automatically take into account the feedback effects of fielder actions on the optical trajectories seen by the fielder model. Such models can be used to show what the optical trajectories of uncatchable fly balls would look like if fielders were using particular kinds of information as the basis of catching.

The plots in Figures 1 and 2 show the optical trajectories that are seen by a fielder model trying to catch fly balls on the basis of information about the balls' vertical optical velocity and lateral displacement. Vertical optical velocity is the rate of change in angle α over time, and lateral displacement (γ) is the angular deviation of the ball from the line of gaze, which is always straight ahead. All trajectories in Figures 1 and 2 are for uncatchable balls

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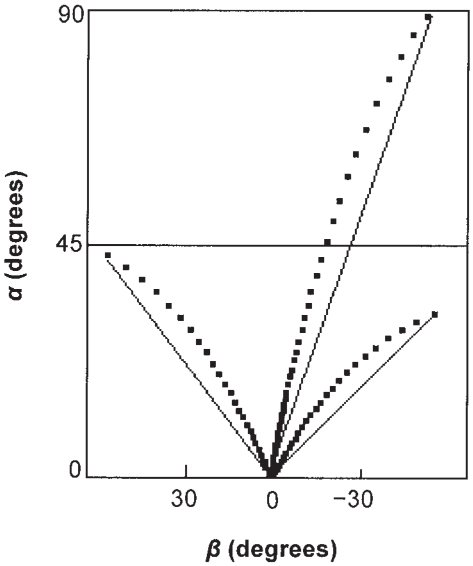

Figure 1. Optical trajectories of uncatchable balls that go over the head of a fielder model controlling both vertical optical velocity and lateral optical displacement. α is the vertical angle above horizontal from the fielder to the ball. β is the horizontal angle between a line from the fielder to home plate and a line from the fielder to the point where the vertical projection of the ball hits the ground.

that go over the head of the fielder model. The trajectories in Figure 1 are plotted in terms of the vertical (α) and lateral (β) optical angle of the ball relative to a fixed point in the visual scene, which is typically taken to be home plate (McLeod et al., 2002, Appendix, p. 1501). The trajectories are linear but slightly downward sloping. The shape of these trajectories is very similar to that of the trajectories reported by Shaffer and McBeath (2002, Figure 8B, p. 344). Note that angle β in Figure 1 is not the same as the variable γ, which is the one controlled by the fielder model.

Shaffer and McBeath (2002) have noted that a model that acts to match the rates of change in α and β could produce linear trajectories like those in Figure 1. The fielder model that produced the linear trajectories in Figure 1 was, indeed, controlling the rate of change in α, but it was not controlling the rate of change in β, and more important, it was not controlling these two variables relative to each other. So the linear trajectories in Figure 1 were produced by a model that was using neither LOT nor the relative rates of change in α and β as the informational basis of catching. Moreover, the nonlinearities in the plots do not depend on changes in where the fielder is looking in rotational space. Such changes have been suggested as one reason why the otherwise linear trajectories for uncatchable balls curve downward near the end of the catch (Shaffer et al., 2003). The model that produced the trajectories in Figure 1 always looked straight ahead at the ball, even as it moved laterally to catch the ball.

Figure 2 shows the optical trajectories in Figure 1 replotted in terms of tanα over time. The trajectories show that tanα increases at an accelerating rate when the ball is hit over the fielder's head. These plots are equivalent to the replots of the Shaffer and McBeath (2002) trajectories that were made by McLeod et al. (2002). Again, the shape of the trajectories in Figure 2 is very similar to that of the trajectories reported by McLeod et al. (2002, Figure 1, bottom panel, p. 1500).

The results in Figures 1 and 2 show that the shapes of optical trajectories can be deceiving. The trajectories in Figure 1 appear to be consistent with LOT theory because they remain linear throughout most of an attempted catch. But the observed linearity of these trajectories is produced by a model that does not use LOT (or constancy of the ratio of rate of change in α to rate of change in β) as the basis of its actions. Similarly, the trajectories in Figure 2 appear to be consistent with OAC theory because the observed acceleration of tanα correctly indicates that the ball is going to go over the fielder's head. But, again, the observed acceleration of tanα is produced by a model that does not use acceleration of tanα as the basis of its actions.

Closed-Loop Analysis of Catching

Researchers have looked at optical trajectories to determine the information that fielders use as the basis of their actions under the assumption that this information is a cue for fielder actions. In fact, the information that fielders use as the basis of action is simultaneously a cue for and a result of action. There is a closed-loop relationship between what the fielder sees—the optical trajectory of the ball—and what the fielder does on the basis of what is seen—the fielder's actions. When this closed-loop situation is correctly analyzed using control theory, we find that the informational basis of catching is not a cue but rather a controlled result of action. In the jargon of control theory, the informational basis of catching is a *controlled variable* (Marken, 2001). To determine the informational basis of catching, it is therefore necessary to determine what optical variables fielders control when catching fly balls. The method used to do this is the control-theory-based Test for the Controlled Variable (TCV; Marken, 1997; Powers, 1973, pp. 232–234).

Testing for Controlled Variables

The TCV starts with a hypothesis about the variable that is being controlled by the behaving system. For example, in the case of

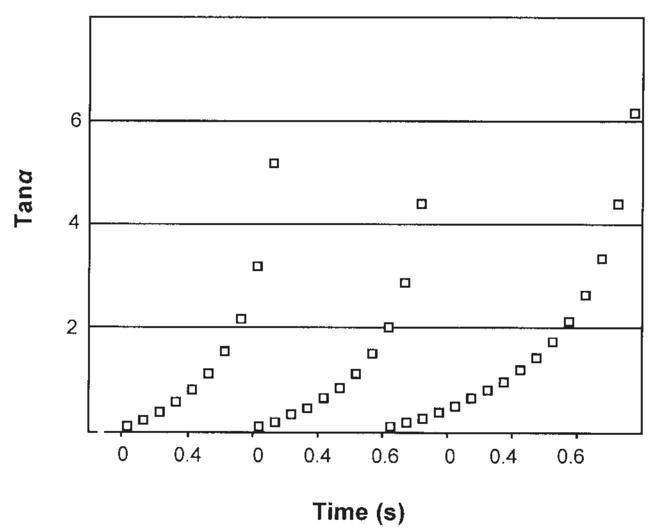

Figure 2. Optical trajectories from Figure 1 plotted in terms of the tangent of the vertical optical angle of the ball (tanα) over time.

catching fly balls, the starting hypothesis might be that the controlled variable—the one controlled by the fielder—is acceleration of tanα. One then applies disturbances to the hypothetical controlled variable and looks to see if these disturbances have the expected effects on the variable. In the case of acceleration of tanα, one could perturb the path of the fly ball in a way that would cause known variations in the acceleration of tanα if the fielder were not acting to keep that variable under control.

One evaluates the effects of disturbances by monitoring the state of the hypothetical controlled variable while known disturbances are being applied. The effects of these disturbances can be measured in terms of the correlation between time variations in the disturbance and concomitant time variations in the hypothetical controlled variable. For example, one can measure the correlation between variations in the disturbance applied to the trajectory of the ball and variations in the acceleration of tanα over time. A high correlation indicates that the disturbance is having the expected effect on the hypothetical controlled variable, because the behaving system is doing nothing to protect the variable from disturbance. A correlation close to zero indicates that the disturbance is not having the expected effect, because the behaving system is acting to protect the variable from the disturbance.

If disturbances do have the expected effects on the hypothesized controlled variable, then that variable is not under control in the sense that it is not being protected from the effects of the disturbances by the actions of the behaving system. If, for example, disturbances applied during a catch have the expected (or something close to the expected) effects on the acceleration of tanα, the hypothesis that acceleration of tanα is the controlled variable can be rejected. In this case, the next step in the TCV is to develop a new hypothesis regarding the controlled variable and to test again by applying disturbances to determine whether this new variable is under control.

If disturbances do not have the expected effects on a hypothesized controlled variable, then that variable is very likely under control in the sense that it is being protected from the effects of the disturbances by the actions of the behaving system. If, for example, disturbances applied during a catch have little or no effect on the acceleration of tanα—acceleration of tanα remains nearly constant—the hypothesis that acceleration of tanα is the controlled variable can be accepted, at least tentatively. The TCV continues until one comes up with a definition of the controlled variable that passes the test in the sense that it is protected from all disturbances that should have an effect on the variable.

Doing the TCV

We can use the fielder model to demonstrate the TCV. We start by imagining that we do not know what information the model is using as the basis of fly ball catching. That is, we place ourselves in the situation we are in when we test to determine the variable controlled by real fielders. We assume that what we know about the behavior of the model is what we know about the behavior of a real fielder. For example, we know that a fly ball traces out a nearly linear optical trajectory, like that in Figure 1, when the fielder runs to catch the ball. So we can start the TCV with the hypothesis that the fielder model is controlling for production of this LOT, which is equivalent to hypothesizing that LOT is a controlled variable.

If LOT is a controlled variable, then disturbances that change the trajectory of the ball while the ball is in flight should have little or no effect on the linearity of the optical trajectory. So we can test the hypothesis that LOT is a controlled variable by applying a disturbance to the trajectory of the ball that would make the LOT nonlinear if LOT were not controlled. We can select such a disturbance and easily apply it to the computer-generated trajectories of the balls caught by the fielder model—in this case, a sinusoidal change in the lateral position of the ball, which acts like a strong wind pushing the ball to the left and to the right during its flight.

Figure 3A shows the optical trajectories of two fly balls, one that was not affected by the lateral disturbance and one that was. The trajectories of the two fly balls would have been exactly the same had the lateral disturbance not been applied to one of them. The effect of the disturbance is clearly visible in the optical trajectory traced out during the catch, particularly in comparison with the nearly linear trajectory produced when no lateral disturbance was present. The effect of the disturbance on the hypothetical controlled variable can be quantified by measuring the correlation between lateral variations of the optical path (variations on β) and variations in the disturbance to that path. This correlation is .98, showing that the disturbance to LOT was almost completely effective. The conclusion of the TCV is that the fielder model does not control LOT. And, indeed, it does not.

The next step in the TCV is to continue looking for the variable controlled by the fielder model. Figure 3B shows the results of testing to see whether lateral displacement from the line of gaze (the variable γ) is a controlled variable. The two traces show lateral displacement over the course of the same two catches shown in Figure 3A. The disturbance appears to have some effect on lateral displacement, but that effect is quite small. The correlation between disturbance and lateral displacement is $-.01$. So the disturbance has very little effect on lateral displacement, which would lead one to conclude that lateral displacement (γ) is a controlled variable. And, indeed, lateral displacement is one of the variables controlled by the fielder model.

The results in Figure 3 show that a disturbance has a large effect on one possible controlled variable, LOT, but little or no effect on another, lateral displacement angle (γ). In this case, after testing only two hypotheses about the variable controlled by the fielder model, we hit on what we know to be one of the variables that is actually controlled by the model, lateral displacement angle (γ). The same type of testing could be done to determine that the other variable controlled by the model is rate of change in α. Control of this variable could be detected by applying disturbances to the vertical component of the ball's trajectory.

It should be noted that the disturbances used in this demonstration of the TCV produce ball movements that would be unrealistically large for a real ball moving through the air. These disturbances were selected for this simulation of the TCV to make their effect on an uncontrolled variable, such as β in Figure 3A, relative to their effect on a controlled variable, such as γ in Figure 3B, visually obvious.

Shaffer, Krauchunas, Eddy, and McBeath (2004) did something very much like the TCV using Frisbees as a means of producing nonparabolic trajectories. The optical trajectories of catches made when there was a large lateral change in the trajectory of the

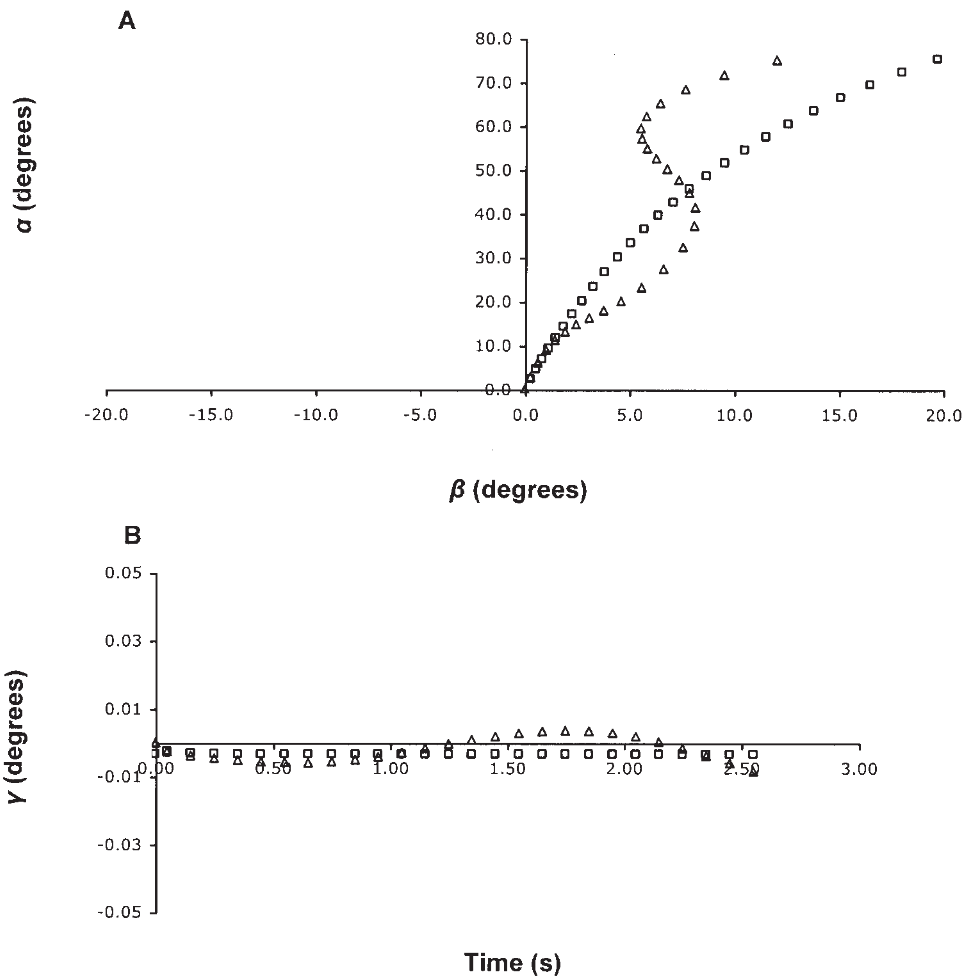

Figure 3. A: Optical trajectory with (triangles) and without (squares) sinusoidal disturbance to the lateral path of the ball. B: Lateral displacement (γ) of the ball image from the line of gaze plotted over time for the trajectories in Panel A.

Frisbee (Shaffer et al., 2004, Figure 4, p. 440) resemble the optical trajectories of laterally disturbed balls caught by the fielder model, like the one shown by the triangle plot in Figure 3A. Shaffer et al. (2004) showed that a double (and, in one case, a triple) LOT could be fit to the optical trajectories observed when there were large midair perturbations, as there were with the Frisbee. A triple LOT would fit the laterally disturbed trajectory shown in Figure 3A rather well, even though these LOTs are not the informational basis of the catching done by the model. This shows again that one cannot determine the informational basis of catching by looking only at aspects of the optical trajectory alone. To determine the informational basis of catching, one must test for the lack of expected effects of disturbances to the aspects of the trajectory that are thought to be under control. That is, one must do some version of the TCV.

Methodological Considerations

When doing the TCV, it is important to apply disturbances that the system is capable of resisting. In other words, the system must be able to successfully control the hypothesized controlled variable. In the case of fly ball catching, this means that the hypothetical controlled variable should be disturbed in a way that does not make it impossible for the fielder to catch the ball. Disturbances that produce uncatchable balls will have a strong effect on the hypothetical controlled variable, but it will be impossible to tell whether this effect occurs because the fielder is not controlling the variable or because the fielder could not control it. In the example TCV shown in Figure 3, both the disturbed and the undisturbed fly ball were caught by the fielder model.

It is also important when doing the TCV, as it is in all experimentation, to be wary of the possibility of confounding. The potential confound of most concern in the TCV comes from the fact that the disturbances can affect the state of more than one possible controlled variable. In the case of catching, for example, disturbances that affect the acceleration of $\tan\alpha$ will also affect the velocity of $\tan\alpha$. To the extent that the actions that protect the acceleration of $\tan\alpha$ from disturbance also protect the velocity of $\tan\alpha$ from the same disturbance, it will be impossible to tell whether the variable under control is the acceleration of tanα or the velocity of tanα.

Removing confounds from the TCV requires ingenuity, as does removing confounds in any experimental testing situation. To remove such confounds, the experimenter must, of course, be aware of them and then be able to produce disturbances that will be resisted only if one variable rather than another is actually under control. In the case of fly ball catching, this will require the ability to generate very specialized disturbances to the trajectory of the ball. One way to produce such disturbances would be to use CAVE technology (Zaal & Michaels, 2003), whereby a computer is used to add precisely calculated disturbances that affect only one hypothetical controlled variable at a time.

It is also important to note that the TCV is done on a person-by-person basis. The TCV does not assume that every person controls the same variables when performing a particular behavior. In the study of catching, for example, the TCV does not assume that all fielders control the same variables. Indeed, one goal of the TCV would be to see whether there is evidence that different fielders control different variables when they catch fly balls. The TCV should be able to detect any individual differences in the informational basis of catching. Indeed, the test could be used to determine whether there are differences across species in the variables controlled when catching (Shaffer et al., 2004). If there are such differences, it would be interesting to see whether catching is accomplished more effectively by controlling some variables rather than others.

Conclusion

McBeath et al. (1995) introduced an important innovation in the study of how fielders catch fly balls by using cameras to capture the optical trajectories of fly balls as seen from the fielder's perspective during catches. These optical trajectories show what fielders see when they run to catch a ball, but they do not show what fielders control while catching. To determine the informational basis of catching, it is necessary to determine the optical variable(s) that fielders control. This can only be done using some variant of the TCV, in which one looks for lack of effects of disturbances to hypothetical controlled variables. The TCV still requires that one monitor what the fielder sees when catching balls: optical trajectories. But the TCV also requires that one look at the relationship between what the fielder sees—the possible controlled variables—and disturbances that should have an effect on what is seen. Aspects of optical trajectories that should be affected by these disturbances but are not are the informational basis of catching.

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