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The Relevance of Action in Perceiving Affordances: Perception of Catchableness of Fly Balls

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The catchableness of a fly ball depends on whether the catcher can get to the ball in time; accurate judgments of catchableness must reflect both spatial and temporal aspects. Two experiments examined the perception of catchableness under conditions of restricted information pickup. Experiment 1 compared perceptual judgments with actual catching and revealed that stationary observers are poor perceivers of catchableness, as would be expected by the lack of information about running capabilities. In Experiment 2, participants saw the 1st part of ball trajectories before their vision was occluded. In 1 condition, they started to run (as if to catch the ball) before occlusion; in another, they remained stationary. Moving judgments were better than stationary judgments. This supports the idea that perceiving affordances that depend on kinematic, rather than merely geometric, body characteristics may require the relevant action to be performed.

One of the assumptions of ecological psychology is that the environment is perceived in animal-relevant terms, that is, in terms of what the animal can do with and in the environment. Perception is seen as an active pickup of meaningful information that specifies the behavioral possibilities of the environment, also called *affordances.* These affordances (Gibson, 1979/1986) are the possibilities for action offered by the environment and the events that occur in it, described with respect to and in terms of the perceiving and acting animal. Ecological psychology claims that it is important for animals to perceive these affordances, so that the control of behavior can be adjusted to the possibilities for action that are supported by the environment.

Most of the affordances that have been derived and investigated have concerned geometric relations between observer and environment (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Mark & Vogele, 1987; Warren, 1984; Warren & Whang, 1987). That research shows that the perception of affordances, such as the climbableness of stairs, is body scaled. Observers perceive environmental properties in terms of their own body dimensions.

Although emphasis has been on geometric units, it is clear that affordances can also depend on time, so that not only geometric but also kinematic (spatiotemporal) relations play a role (Warren & Whang, 1987). Such affordances can be found, for example, in traffic situations such as crossing a busy street, where not only the to-be-crossed distance is important but also the time that is available for covering this distance safely (Demetre et al., 1992; Lee, Young, & McLaughlin, 1984; Young & Lee, 1987). Whether a traffic situation affords safe stopping by braking, as discussed by Lee (1976) and Stewart, Cudworth, and Lishman (1993), provides another example of such an affordance. In fact, in any situation in which a certain distance is to be covered in a specific time, the affordance can be described in kinematic terms. Therefore, in sports, in which players have to receive passes or catch fly balls, examples abound. Again, the catchableness of a baseball or a football depends not only on the distance that is to be covered but also on the time that is available for covering this distance.

Bootsma, Bakker, van Snippenberg, and Tdlohreg (1992) and Peper, Bootsma, Mestre, and Bakker (1994) have already investigated the perception of catchableness of balls passing the observer laterally. In the situation they examined, ball catching required lateral hand movement only, without sideward bending or locomoting. With respect to this task, scaling to arm length is sufficient, and observers' judgments of critical passing distance appeared reasonably accurate.

The focus of this article is on the perception of catchableness of fly balls projected in the sagittal plane of the catcher, the catching of which usually requires locomotion. To catch a fly ball in baseball, the fielder must gear his or her locomotory actions to the information from the flight of the ball in such a way as to arrive at the landing site at or before the time the ball arrives. The boundary that separates catch-

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able and not catchable depends on the locomotory capabilities (speed and acceleration) of the would-be catcher. Hence, pure body scaling is not sufficient. Describing the boundary of catchableness in terms of, for instance, eye height, where this boundary is, say, three eye heights away, does not solve the problem. Instead, the boundary must be described both in terms of the distance and the available time, that is, in terms of the speed (distance divided by time), acceleration (twice the distance divided by time squared), or both of the catcher's running. In other words, whether a ball is catchable depends on the actions the catcher–perceiver can develop, not his or her eye height, leg length, or arm length (even though they are surely correlated). Only if action scaling occurs is there a commensurability between the affordance, a property of the environment, and the effectivity, the complementary property of the animal (Shaw, Turvey, & Mace, 1982; Turvey, 1992).

An interesting question with respect to this action scaling is whether perceptual information about the boundary of catchableness is available when an observer is standing still, that is, when the observer is not performing the (in this case, locomotory) action. Let us work out the details of this issue with respect to vertical optical acceleration, a potential information source in the fly ball situation in which there is no lateral motion of the ball relative to the catcher. Vertical optical acceleration is the acceleration of the projection of the center of the ball on a vertical image plane and tells the catcher what action is necessary to catch the ball (see Appendix for details). The sign of vertical optical acceleration specifies the direction (forward or backward) in which the catcher should accelerate (Babler & Dannemiller, 1993; Chapman, 1968; Michaels & Oudejans, 1992; McLeod & Dienes, 1993). Getting and keeping vertical optical acceleration near zero (that is, below the detection threshold; see Babler & Dannemiller, 1993) during the entire ball flight will bring the catcher to the right place at the right time to intercept the ball. It is our working assumption that the informational value of optical acceleration is based purely on its presence (values above the detection threshold) or absence (values below the detection threshold).[1] No optical acceleration means that the catcher is on a collision course with the ball; the presence of optical acceleration indicates that the catcher should adjust his or her movements (accelerate forward or backward depending on the sign of the acceleration). Thus, the catcher need not predict the landing location of the ball to make the catch; he or she need simply monitor the presence or absence of optical acceleration and act accordingly.

Although an elegant source for the guidance of locomotion toward the future landing location of the ball, it seems unlikely that optical acceleration provides information about the boundary of catchableness when the observer is standing still. Leaving aside the situation in which the observer is standing still and optical acceleration is zero (specifying that the ball will arrive at the eye and is therefore catchable), catchableness is not specified by optical acceleration when the observer is stationary. To catch balls that do not land at the catcher's initial position, movement is necessary. To scale the trajectory against possible actions, it must be the case that information about both is available, either from perceptual information alone or from perceptual information combined with knowledge from memory. Rather than assuming the latter, we agree with Mark et al. (1990) that actors determine their capabilities anew each time they perform an action. They do so by picking up information about their capabilities, relative to the environment, that is revealed by their own actions (Mark et al., 1990).

We propose that specification of catchableness on the basis of vertical optical acceleration occurs as follows. An optical acceleration of zero (below the detection threshold) at a certain moment informs the catcher that the ball is catchable, assuming that he or she can maintain the current running speed (though see a proviso in the Appendix). In contrast, if the catcher has reached maximum running speed and optical acceleration is still not zero (not below the detection threshold), this informs the catcher that the ball is not catchable. These two situations elucidate the relational character of optical acceleration, showing that optical acceleration is neither about ball trajectories nor about action possibilities but about their combination. It informs about the motion of the ball relative to the locomotory actions of the catcher. Thus, with respect to balls that do not land at the initial position of the catcher, which balls are catchable and which are not is specified only when a catcher is running.

Whereas the actual catchableness of a fly ball is dependent on both distance and time, it remains to be seen whether perceptual judgments of catchableness also reflect both of these variables. It is possible that judgments of catchableness reflect distance alone—the edge of catchableness is seen at a certain distance away, as shown in Figure 1A, in which the division of space–time into catchable and noncatchable regions would be determined by this specific critical distance. Judgments of catchableness could also reflect both distance and time, as is the case when scaling takes place according to, say, the average running speed that should be developed; here the critical value would be a ratio of landing distance to flight time (Figure 1B). Another possibility is that judgments reflect the possible acceleration of the observer, in which the critical ratio is twice the distance divided by flight time squared (Figure 1C). In both of these latter cases, there is some critical value, either the maximum average running speed or the maximum acceleration, that segments space–time into catchable and noncatchable regions. Thus, if on the basis of the distance–time combination of a certain ball, the required running speed or acceleration exceeds the possible running speed or acceleration, the ball in question is not catchable. As mentioned, the dependence of actual catching on such factors as accel-

[1] We do not believe that actual value of optical acceleration is informative, because of its ambiguity with respect to landing location; trajectories with different values of optical acceleration, given different heights and trajectories (see Appendix Equation A3), can still lead to the same landing position. Thus, even if perceivers could discriminate between different values of optical acceleration, this would not be useful for predicting where the ball will land.

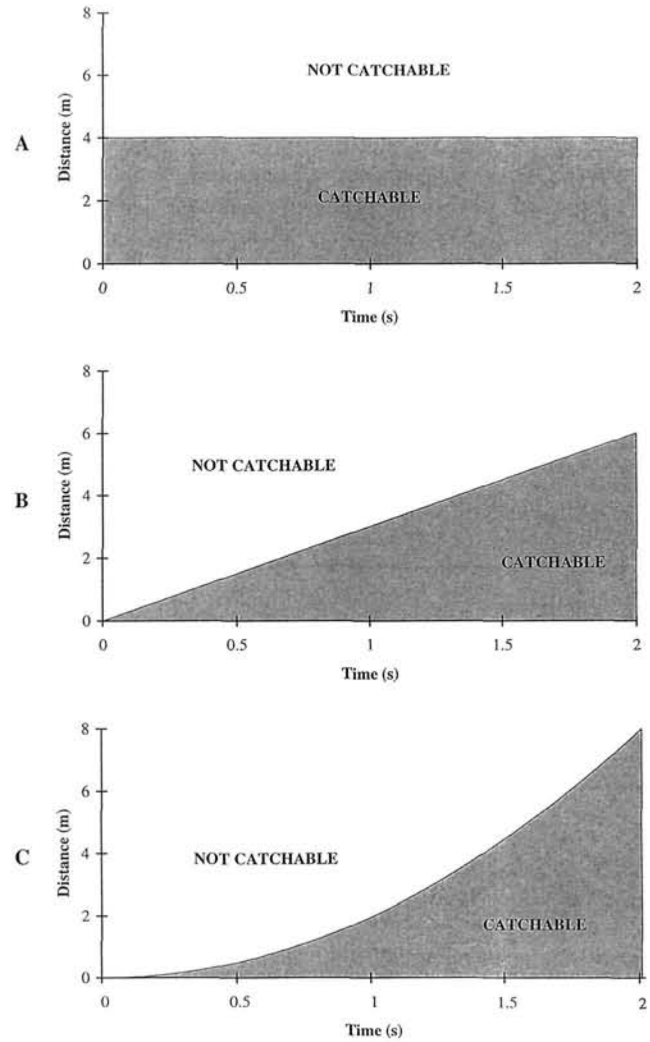

Figure 1. The division of space–time into catchable and not-catchable regions by either distance (A, distance = 4), velocity (B, distance = 3 · time^2), or acceleration (C, distance = 2 · time^2). These values were arbitrarily chosen.

eration may or may not be reflected in perceptual judgments.

The overall goal of the present study was to test whether or not, in the case of this "kinematic" affordance, catchableness, perceptual information about the perceiver's own actions has to be available for this affordance to be perceived. In other words, is it possible for an observer to perceive catchableness accurately without performing the required action, as it appears to be for affordances for which geometric scaling is appropriate?

Experiment 1

Experiment 1 examined whether stationary observers, despite the fact that vertical optical acceleration does not specify catchableness to them, can accurately perceive catchableness, perhaps on the basis of other optical information or on the basis of perceptual information in combination with knowledge about potential actions stored in memory. A good perceptual performance would support either of these two latter possibilities, and it would undermine our hypothesis that accurate perception of catchableness is only possible on the basis of vertical optical acceleration conjoint with (other) perceptual information about the running actions of the catcher. An attempt was also made to find out which variable—distance or the to-be-developed velocity or acceleration—best captures the transition from catchable to not catchable, both in actual catching and in the perception of catchableness. It was expected that, with respect to actual catching, acceleration would do best. With respect to perceptual judgments, any of the three variables was deemed possible as the best predictor of the judgments.

Because in general it appears that experienced athletes are more accurate than novices in responding to skill-specific information (Abernethy, 1990a; 1990b; Abernethy & Russell, 1987; Jones & Miles, 1978; for an overview of differences between experienced athletes and novices see Abernethy, 1994) and to increase the likelihood of having participants skilled in perceiving the catchableness of fly balls, this experiment tested both expert outfielders and nonexperts. If judgments of catchableness are based on stored knowledge, then differences are to be expected between nonexperts and expert outfielders because the quality of stored information, amount of stored information, or both ought to be different in both groups. If, on the other hand, judgments are based on vertical optical acceleration, then, due to a lack of specification of catchableness, equally poor performance is to be expected for both groups.

Method

Participants. Twelve male observers, 6 nonexperts and 6 expert outfielders, participated in the experiment. On average the expert outfielders had 15 years of competitive baseball experience (range = 7–21 years). One of the outfielders played in the Major Leagues in the United States. The remaining 5 played in the Netherlands: 3 in the professional league and 2 one league lower. The nonexperts did not have any baseball experience, although a few had experience in other ball sports such as table tennis, tennis, and soccer. The average age of the entire group was 27 years (range = 22–44 years). All participants reported normal or corrected-to-normal vision. They were paid a small fee for their participation.

Design. The observers were tested in two conditions, a perceiving-only condition and an actual catching condition, always in that order, to prevent observers from using actual catching performance to make perceptual judgments. In the first condition, the task of the observers, who remained stationary, was to indicate as quickly as possible whether a ball could be caught if they had been allowed to run freely. In the catching condition, the task of the observers was to attempt to catch the balls before the bounce. In each condition 60 balls were projected preceded by 10 practice trials. Half of the balls landed in front of the observer and half landed behind him, in random order. The distances to which the balls were shot were adjusted according to observers' performance (in catching and judging) to ensure that both categories (catchable and not catchable) were sufficiently populated.

Experimental setup. The experiment was carried out in a gymnasium (height = 9 m), where a machine shot tennis balls from behind an opaque screen (height = 1.2 m) toward observers (see Figure 2). The balls, projected in the sagittal plane of the observer, had near parabolic flight trajectories and landed either in front of or behind the observer's initial position. The initial machine-to-observer distance was 18 m.

The trajectories of the balls, along with the movements of the observer–catcher, were videotaped at 50 Hz with two cameras, one S-VHS Blaupunkt camcorder and one Panasonic camera connected to a S-VHS Blaupunkt video recorder. Both cameras were set up perpendicular to the plane in which the balls were shot, in such a way that together they covered the entire length (40 m) and height (9 m) of the gymnasium (see Figure 2). To obtain identical time codes in the images of both videotapes an external sync and a time code generator were used.

Procedure. In the perception-only condition the observer was instructed to move his arm forward if he judged a ball catchable and backward if he judged a ball not catchable. He was told to do so irrespective of where the ball eventually landed, in front of him or behind him. Both the distance the ball traveled and the time the ball was in flight were manipulated. Flight time was varied by shooting the balls to three different heights: the maximum height possible without contacting the ceiling (about 8 m high), approximately 75% of this maximum height (about 6 m high), and approximately half this height (about 4 m high). The first 36 balls were projected to a range of 7–12 m in front of the observer and 4–9 m behind the observer, evenly divided over the three possible flight times. We used different distances to make the two conditions comparable; catchers can cover more distance per unit time running forward than backing up. The order of the first 36 balls (18 in front, 18 behind) was randomized. On the basis of the responses to the first 36 balls, the experimenters determined which distance–time combinations should be used for the remaining 24 balls (12 in front, 12 behind) to ensure sufficient numbers of judgments in each category. One of the experimenters each time indicated when the next ball was about to be projected.

In the catching condition the first 18 balls landing in front were projected in the range 3–12 m. The catchers were allowed to run freely from the initial position (18 m from the point of projection). The remainder of the procedure was similar to that of the catchableness condition; ranges were adjusted such that the transition from catchable to not catchable was somewhere in the middle. As a result, the ranges used in the two conditions could differ both between and within observers.

Results and Discussion

For all throws in both conditions the distances between the initial position of the observers and the landing positions of the balls (where the balls were caught or could have been caught, thus not where they hit the ground) were determined from the videotapes. These running distances (*D*s) are the distances the observers ran (or would have to run) to catch the balls. The flight times of the balls were also determined (to an accuracy of 20 ms, related to the frame rate of the video).

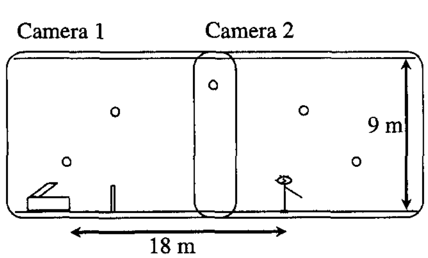

Figure 2. A schematic (side view) representation of the experimental situation. The perceptual condition is depicted in which an observer responded by moving his left arm (visible on video) forward or backward.

In our first analysis we attempted to determine which variable (distance, velocity, or acceleration) best captured the transition from catchable to not catchable in each of the two conditions. The responses of the observers in the catchableness condition (judged catchable or not catchable)[2] and in the catching condition (caught or not caught) were plotted as a function of three variables: running distance (D), running distance over time (D/T), and running distance over time squared (D/T^2); representative examples are shown in Figure 3.

Twelve such plots were obtained for each participant, the combination of two conditions (judging and catching), two landing position possibilities (in front and behind), and three variables (D, D/T, and D/T^2). Using a least squares iterative fit procedure, the best possible logistic function (see Bootsma et al., 1992; Peper et al., 1994) was fitted onto each of these plots to measure the critical points and the slopes at these points. The logistic function is represented by the following equation:

$$y = 1/(1 + e^{-k(c-x)}), \quad (1)$$

where x is the variable (D, D/T, or D/T^2), c is the critical value of x at which the transition from one type of response (catchable or caught) to the other type of response (not catchable or not caught) occurs, and k is a measure of the slope at point c. Examples of the fits can be seen in Figure 3, in which the dashed lines represent best fits. Correlation coefficients of the fits were also computed.

Both the slopes and the correlation coefficients give an indication of how abrupt the transition is from one type of response to the other. The steeper the slopes and the higher the correlation coefficients, the more abrupt the transition (i.e., the less variable the responses). Presumably, the predictor variable (either D, D/T, or D/T^2) that best captures the transition from catchable to not catchable should produce the least variable response pattern—steeper slopes and higher correlations. Because the slopes obtained with the different variables have different units (either m, m/s, or m/s^2), they do not permit comparison. Therefore, to test which variable suits the data best the correlation coefficients were used. To normalize the distribution of the correlation coefficients Fisher Z transformations were computed.

Once the best-fitting variable(s) is established, one can

[2] Recall that the task of the observers was to respond as quickly as possible. Movement initiation times of the responses (also gathered from videotape) revealed that observers tried to do this. On average, the nonexperts and experts initiated their responses after 786 (SD = 231) and 712 (SD = 130) ms, respectively; the difference was not significant, $F(1, 10) = .53$. Taking into consideration that flight times were about 2 s, responses were, at least, initiated well before the balls landed.

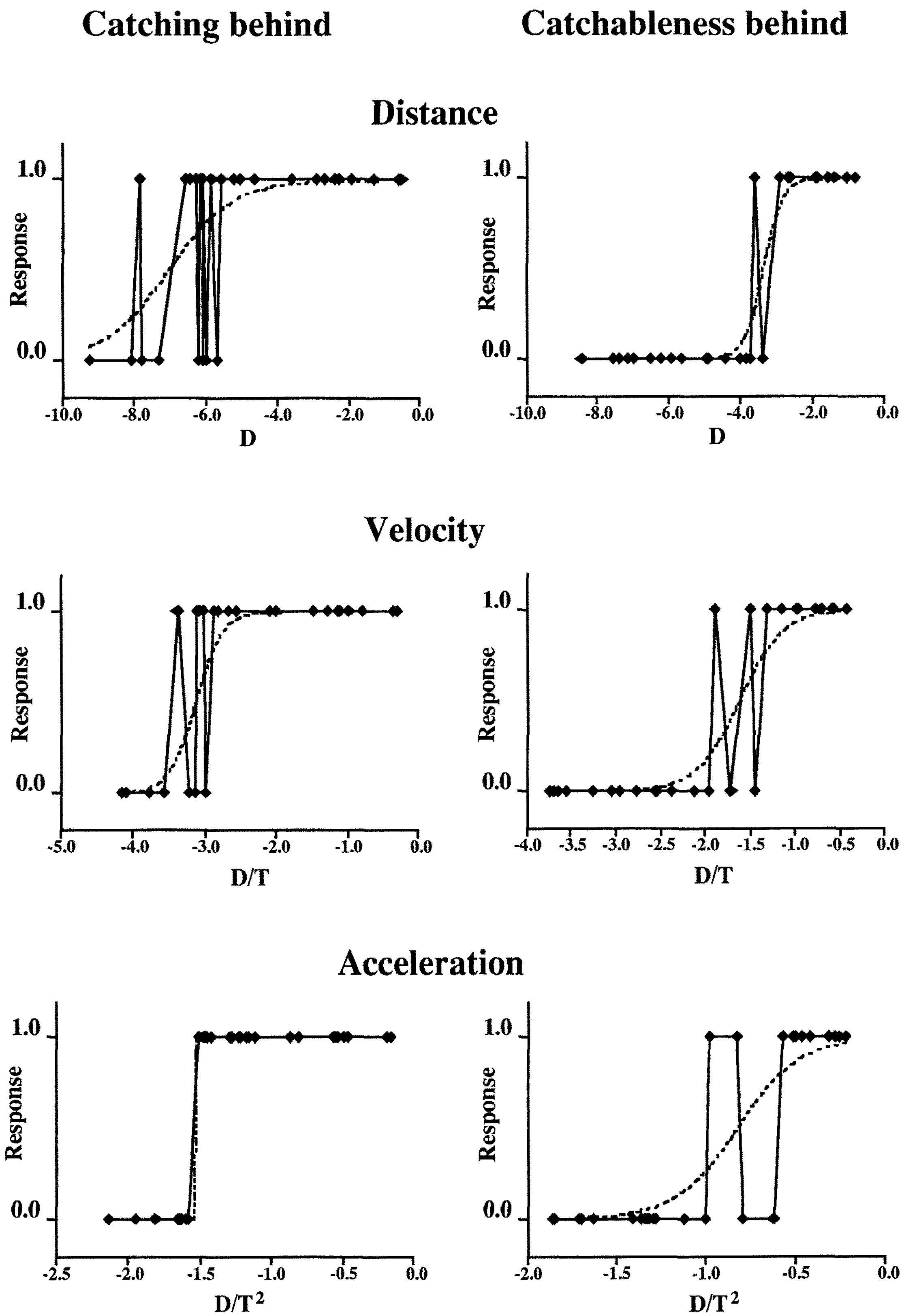

Figure 3. Graphic representation of the responses of one observer with respect to balls landing behind him plotted against *D* (running distance), *D/T* (running distance over time), and D/T^2 (running distance over time squared). Zeros indicate balls not caught (or judged not catchable); 1s indicate balls caught (or judged catchable). Responses in both the catching behind (left) and the catchableness behind condition (right) are depicted. The dashed lines represent the best-fitting function to the data (see text for details).

compare the critical values of the catchableness and the catching condition for each observer to determine how accurate the observers were in judging whether the projected balls were catchable.

Goodness of fit. A 2 (Expertise [experts, nonexpert]) × 2 (Landing Position [front, back]) × 3 (Variable [*D*, *D/T*, D/T^2]) × 2 (Task [catching, judging]) repeated measures analysis of variance (ANOVA), with expertise as the only between-subjects factor was performed on the Fisher Z values of the correlation coefficients. It revealed that the fits were better in the catching ($Z = 1.40$) than in the catchableness condition ($Z = .81$), $F(1, 10) = 47.01$, $p < .001$; these Z values correspond to R^2 values of .78 and .45, respectively. Predictably, the transition from catchable to not catchable is more abrupt and less variable in the actual catching situation than in the perceptual judgment situation.

There was a significant effect of variable, $F(2, 20) = 8.86$, $p < .005$. The variance accounted for by acceleration ($R^2 = .69$, $Z = 1.20$) was significantly higher than that accounted for by distance ($R^2 = .54$, $Z = .94$), indicating that acceleration, as predicted, better captured the boundary of catchable and noncatchable than distance. Newman–Keuls post hoc analyses revealed a difference between the velocity correlations ($R^2 = .67$, $Z = 1.16$) and those of distance ($p < .01$), but not between velocity and acceleration. The significant interaction of variable with task (catching vs. perceiving only) indicated that the superiority of acceleration and velocity held only for the catching condition ($F = 5.81$, $p < .05$). As can be seen in Figure 4, distance alone was just as good a predictor in the perceptual condition as velocity or acceleration. In real catching, the transition from catchable to not catchable appears to incorporate time, as the physics of the situation would predict, but no such superiority is seen in the perceptual condition.

Expertise was not a significant factor in any of the above analyses; neither the perceptions nor the actions of the outfielders were less variable than those of the nonexperts.

Critical values. The perceptual (catchableness) critical values were scaled to the actual (catching) critical values by taking the ratio of the two. This was done for distance, velocity, and acceleration. All of the analyses yielded the same results. We present only those for acceleration, given the physics of the situation and the goodness-of-fit results indicating that the threshold for catching was most reliably related to acceleration. Table 1 presents these ratios. Perfect perceptual performance would have resulted in ratios of 1. Values greater than one mean that the observer indicated that he could catch balls his actual catching performance indicated he could not; values less than 1 indicate the converse. Most of the observers, nonexpert or expert, were not very accurate in judging the catchableness of the balls. In both groups there was one observer who indicated he could catch balls that required almost twice the acceleration he was actually shown to develop during catching. Four of the 12 observers had scaled critical values close to 1; the others were at least 15% off. Comparison with the scaled critical values that were found in studies with "geometric" affordances makes clear that performance found here is considerably less accurate. All scaled critical values of previous research fall within the range 0.8 and 1.2, even those that are considered inaccurate (Bootsma et al., 1992; Carello et al., 1989; Konczak, Meeuwsen, & Cress, 1992; Mark, 1987; Mark et al., 1990; Mark & Vogele, 1987; Peper et al., 1994; Warren, 1984; Warren & Whang, 1987).

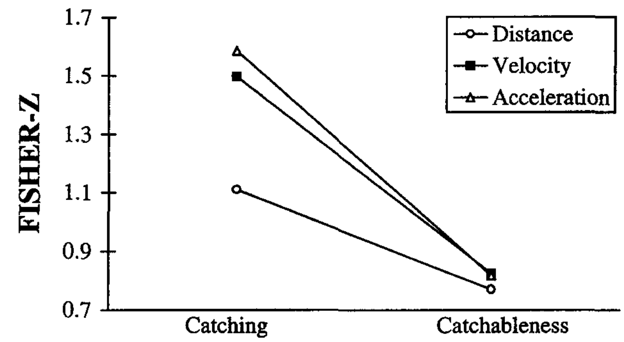

Figure 4. Relative quality of the fits of distance, velocity, and acceleration for the conditions in Experiment 1. The higher the Z values, the better the fit.

Table 1 also shows that there was a large difference between scaled critical values for balls landing behind the observers and those obtained for balls landing in front of them. Again, this is true for both the nonexperts and the experts. A 2 (Expertise) × 2 (Landing Position) repeated measures ANOVA on the scaled perceptual critical values was performed. The difference between balls landing behind and balls landing in front was indeed significant, $F(1, 10) = 10.94$, $p < .01$. The mean scaled critical value for balls landing in front of the observers is 1.31, whereas the mean is .73 for balls landing behind them (see also Table 1). Thus, whereas on average the catchableness judgments in front were characterized by a considerable overestimation, the behind judgments showed a more or less equal underestimation. It is not clear to us why this difference between back and front judgments occurred.

As was to be expected from Table 1, there was no significant effect of expertise, $F(1, 10) = .004$, indicating that the expert outfielders were not different from the nonexperts in judging catchableness. So even the average baseball experience of 15 years did not provide outfielders with the ability to judge catchableness of these balls accurately when they have to remain stationary. To make sure that a possible expertise effect was not obscured by the fact that scaled critical values above 1 canceled out values below 1. A 2 (Expertise) × 2 (Landing Position) repeated measures ANOVA on the absolute error percentages from 1 was also executed. However, no effect of expertise emerged, $F(1, 10) = .045$.

To reiterate, the correlation coefficient data suggest that acceleration is the critical variable determining the transition from catchable to not catchable, though not unequivocally (because acceleration fits were not statistically better than velocity fits). The correlation coefficient data also show that perceptual judgments of catchableness

Table 1
Scaled Critical Values (Ratios of Perceptual and Actual Catching Critical Values) With Respect to D/T^2 for Each Nonexpert and Expert in Experiment 1

	Nonexperts		Experts	
Participant	Front	Back	Front	Back
1	1.31	0.93	1.24	0.76
2	0.69	0.99	1.44	0.54
3	1.47	0.59	1.50	1.01
4	1.51	0.59	1.90	0.75
5	0.66	1.21	0.97	0.80
6	1.83	0.39	1.15	0.20
M	1.25	0.78	1.37	0.68
SD	0.43	0.28	0.30	0.25

reflect time poorly. With respect to the boundary of catchableness, stationary observers are not very accurate in judging whether a specific fly ball is catchable, not even when the observer is an expert outfielder. Thus, it appears that stationary observers cannot instantaneously determine whether they could run to the interception point in time to catch a ball before the bounce. Information specifying the catchableness of a ball is either not available to, or not detected by, stationary observers. As indicated earlier, vertical optical acceleration relative to a stationary observer does not provide the observer with the necessary information about the boundary of catchableness. It now appears that stationary perceivers do not successfully rely on other information, either other perceptual information or information stored in memory, to determine whether or not a ball is catchable.

Experiment 2

We contend that the failure of stationary observers to perceive the catchableness of fly balls is due to the absence of information about and relative to the observer's potential and required actions. Without such information, catchableness of balls landing in the catchable to not catchable transition area is not specified and, as is supported by the results of the first experiment, there is no reason to believe that this information is stored somewhere in memory or available otherwise when the observer is stationary. Experiment 2 examined whether judgments of catchableness improve when observers are moving, that is, when information about the observer's actions is also directly available.

Because Experiment 1 revealed that experts were no better than nonexperts in perceiving catchableness, Experiment 2 used nonexperts only. In addition, rather than asking observers to classify a ball as rapidly as possible, we sought tighter control on their visual exposure. Viewing time was limited by occluding vision.

Method

Participants. Twelve male participants (with no competitive baseball experience) participated in the experiment. Their average age was 24 years (range = 18–33). All participants reported normal or corrected-to-normal vision. They were paid a small fee for their participation.

Design. The observers were tested in three conditions. Each condition consisted of 10 practice trials and 30 experimental trials. The first condition, the stand condition, is comparable to the perceptual judgment condition of Experiment 1. The observer was standing still at the initial position and he was not allowed to locomote. The observer wore Plato liquid crystal display (LCD) spectacles that could be shut and opened with good (3–5 ms) temporal precision. The glasses were normally transparent. One second after the ball was projected, the glasses shut. The observer then had to indicate, verbally this time, whether the projected ball would have been catchable, had he been allowed to run freely. Certainty ratings were also given as one of three possibilities: very certain, certain, and uncertain. The LCD glasses remained opaque for 4 s, after which they became transparent again. The second condition, the move condition, differed from the stand condition in one important way: the observer started to run as if he were trying to catch the ball; again the glasses closed 1 s after ball release. In the third condition, the catching condition, the observer's task was to catch the balls before the bounce. This catching condition was always the last condition, whereas the order of the other two conditions was reversed with every new observer. To make conditions as comparable as possible, the catchers also wore LCD spectacles in the catching condition, but they remained transparent.

Experimental setup. Because of the wire trailing from the LCD glasses (thus, for the sake of safety), it was decided to project all balls in front of the observer. Although this eliminates the uncertainty about the proper direction in which to run, it does not jeopardize the comparison between judgments in the stand and the move conditions because there is no reason to believe the three conditions would be differentially affected.

The experiment was executed in the same gym as the first experiment. Tennis balls were machine-projected from behind an opaque screen (height = 1.2 m) toward the observers (see Figure 2). Balls were again shot in a sagittal plane. The observer's initial position was 25 m from the ball projection machine (though for two observers it was later adjusted; see Procedure).

The landing or catching locations of the balls were videotaped at 50 Hz with one S-VHS Blaupunkt camcorder connected to a S-VHS Blaupunkt video recorder. The camera was set up perpendicular to the plane in which the balls were shot. With help of the Alpermann & Velte Time Code 30 generator, a Vertical Interval Time code (VIT code, a unique time code) was written into the invisible part of each of the fields of the videotapes with an accuracy of 20 ms. The onset of each ball flight was made visible on videotape by an ongoing light emitting diode (LED) that was triggered by the passage of the ball through a slotted Opto Switch (comprising an infrared source and integrated photo detector) at the end of the barrel of the ball projection machine. The delay between passage of the ball through the Opto Switch and the first video frame in which the LED was on was also registered in milliseconds by an M-24 Olivetti personal computer. The ongoing LED, the LCD glasses, and the Opto Switch were all connected to this computer.

Procedure. During the practice trials, balls were projected according to a simple staircase method to get a rough approximation of where the transition was from one kind of response (judged catchable or caught) to the other kind of response (judged not catchable or not caught). During the experimental trials balls were shot to various distances from the tentative critical point that was obtained, roughly from 5 m in front of this point to 5 m behind this point with steps of 1 m. Three balls were projected toward the critical point itself, two balls were projected to each of the distances 1 m from the critical point, and to each of the remaining distances (2, 3, 4, and 5 m from the critical point) one ball was shot. For 2 participants, the tentative critical points of the two perceptual conditions were such that it was necessary to move them 4 m backward so that in those conditions their initial distance to the point of release was 29 m; for an additional observer this was the case in the stand condition only.

The flight time of the balls was manipulated by projecting them to two heights, the maximum height possible without contacting the ceiling (about 8 m) and approximately 75% of this height (about 6 m). In total 30 experimental balls were projected in each condition. The 30 distance–time combinations were randomized within condition.

On each trial, one of the experimenters indicated that the next ball was about to be projected. During the entire experiment observers wore earplugs to deter them from using auditory information to learn about actual bounce location; however, the sound was not completely shut off.

A frame-grabber and digitizing program determined all necessary variables from the videotape. The pixel coordinates of the landing or catching locations of the balls were stored and later translated into real-world coordinates using the Direct Linear Transformation method (see, e.g., Miller, Shapiro, & McLaughlin, 1980; Shapiro, 1978). On the basis of the VIT codes and registered time delays the flight times of the balls could also be obtained. In the move condition, the head positions of the catchers after 1 s (when the glasses shut) were also measured.

Results and Discussion

The determination of the boundary of catchable and noncatchable in the two perceptual conditions, stand and move, was done using six ratings (instead of just two responses, catchable and not catchable, of Experiment 1). Each combination of response and certainty rating was given a value, *catchable/very certain* = 5, *catchable/certain* = 4, and so on, until, *not catchable/very certain,* which was given the value zero. These ratings were again plotted against the three variables *D, D/T,* and D/T^2, and fitted to the following equation:

$$y = 5/(1 + e^{-k(c-x)}), \qquad (2)$$

which is equal to Equation 1, except that the numerator is 5 (instead of 1), representing the maximum value a combination of response and certainty rating could adopt. In Figure 5 two representative examples are presented in which responses are plotted as a function of D/T^2 and the best fits are depicted by the dashed lines. The fitting in the catching condition was, of course, identical to that of Experiment 1 because the data were dichotomous; plots of the catching performance (caught or not caught) as a function of either *D, D/T,* or D/T^2 were fitted according to Equation 1. Perceptual critical values were scaled to the actual catching

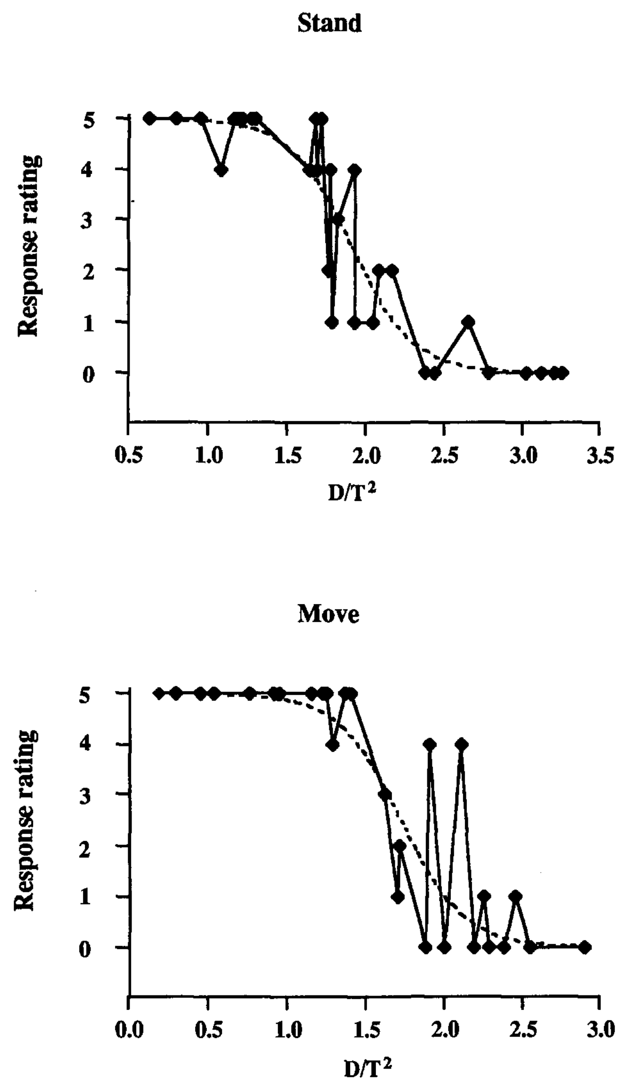

Figure 5. Graphic representation of the response ratings of one observer plotted as a function of D/T^2 for both the stand and the move conditions of Experiment 2.

critical values. The obtained scaled critical values and the correlation coefficients of the fits were analyzed.

Goodness of fit. A 3 (Variable) × 3 (Condition [stand, move, catch]) repeated measures ANOVA on the Fisher *Z* values of the correlation coefficients of the fits revealed a significant main effect of variable, $F(2, 22) = 4.53$, $p < .025$. As in Experiment 1, better fits were found for acceleration ($R^2 = .81$, $Z = 1.48$), compared with distance ($R^2 = .75$, $Z = 1.31$). Again, the velocity correlations ($R^2 = .80$, $Z = 1.44$) also differed from the distance correlations but not from those belonging to acceleration (Newman–Keuls post hoc analysis, $p < .05$).

In contrast to the first experiment, no effect of condition was revealed; the fits for the catching condition ($R^2 = .84$, $Z = 1.57$) were not significantly better than either the stand ($R^2 = .73$, $Z = 1.27$) or the move condition ($R^2 = .78$, $Z =$

1.39). However, a comparison of the two experiments is confounded by the fact that the perceptual conditions in Experiment 2 were fitted to six response ratings (the combination of responses with certainty ratings), whereas actual catching had just two responses.[3]

Another important difference with Experiment 1 is that the interaction between the factors variable and condition was not significant in this second experiment, $F(4, 44) = .014$. In the first experiment it appeared that better fits on the basis of acceleration and velocity were only found in the catching condition. In the perceptual condition Fisher Z values were about equal for distance, velocity, and acceleration (see Figure 4). Figure 6 shows that in the current experiment the differences between acceleration and distance and between velocity and distance fits are existent in all three conditions, indicating that in this case perceptual judgments, too, reflected both distance and time.

Critical values and error percentages. To determine whether judgments of catchableness differ in the stand and move conditions, the scaled critical values (perceptual values divided by actual catching values) were examined. Again, critical ratios of all three variables showed the same pattern of results, so we present here only those based on acceleration (see Table 2).

The absolute error percentages from 1 (| scaled critical values −1 | × 100%) were computed for each observer in each condition and analyzed with a paired *t* test. The difference between the accuracy in the stand condition (percentage error = 36.8) and the move condition (percentage error = 20.1) was significant, $t(11) = 2.71$, $p < .025$. On average, the percentage error decreased by almost half when observers were allowed to run in the direction of the future landing location of the ball prior to making judgments about its catchableness.

Locomotion in the motion condition. To investigate the basis of the above difference, we examined how far observers actually ran in the 1 s the ball was visible. This was only possible for 10 of the 12 participants (the 2 who were moved to 29 m from the ball machine were not visible on video). On average, the 10 observers were 1.82 m away from their initial positions when the glasses closed ($SD = .51$). This is about one fifth of the average distance that had to be covered to catch the balls. The average horizontal distance between ball and catcher at the moment the glasses became opaque was 15.83 m ($SD = .68$). Correlation coefficients between the distances that were run in this first second and the distances that should have been run for successful catching revealed no relation ($r = .13$, $SD = .19$). Thus, observers did not run further in the first second with respect to balls landing further away than to balls landing closer. Nor did the distances run differ between balls judged catchable and not catchable (1.84 and 1.80 m, respectively), $t(9) = .18$, *ns.*

The fact that observers covered only a small distance suggests that the improvement in the move condition was due to the extra information created by the locomotion, and not to something else (e.g., getting closer to the ball).

Thus, the results are in agreement with the expectation that when running is permitted, perceptual information about the observer's actions makes it possible for an observer to judge more accurately whether a ball is catchable. It further supports the idea that rather than having stored knowledge about action capabilities, actors determine their capabilities anew each time they perform an action. Only when the fly ball catcher is running is information about his or her actions directly available. It now appears that catchers can use this information to judge catchableness.

Table 2
Scaled Critical Values With Respect to D/T^2 for Each Participant in Each Condition in Experiment 2

Participant	Condition: Stand	Condition: Move
1	1.49	1.24
2	1.32	1.37
3	1.69	1.24
4	1.30	1.08
5	1.28	1.15
6	0.87	1.07
7	1.64	1.38
8	1.51	0.97
9	0.94	1.34
10	1.44	0.90
11	1.08	0.99
12	1.47	1.39
M	1.34	1.18
SD	0.26	0.17

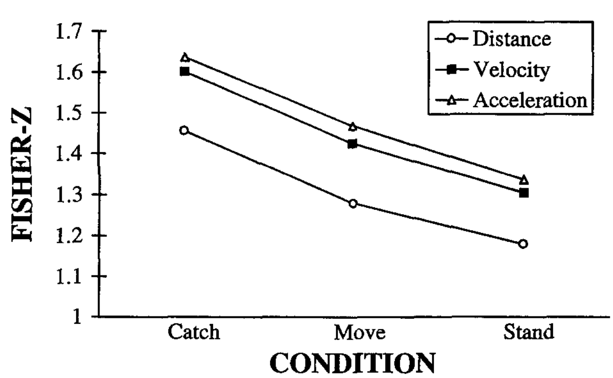

Figure 6. Relative quality of the fits (Z values) of distance, velocity, and acceleration for the three conditions—stand, move, and catch—in Experiment 2.

[3] Comparison of correlations coefficients of the fits based on six ratings with those based on two responses for the perception condition alone in Experiment 2 revealed that indeed significantly more variance of the data was accounted for by the fits based on six ratings ($Z = 1.27$ for stand, $R^2 = .73$; $Z = 1.39$ for move, $R^2 = .78$) than by the fits based on two responses ($Z = 1.11$), $t(35) = 2.90$, $p < .005$ for stand, ($Z = 1.10$), $t(35) = 12.71$, $p < .001$ for move; $R^2 = .65$ and .64, respectively. Thus, the improvement of the fits in the perceptual conditions between experiments may explain the absence of a condition effect in Experiment 2.

General Discussion

Research into affordances is characterized by a search for reference frames that can be used to scale the environment in a way that is relevant for perceptions and actions of animals (Turvey, 1992; see also 1986). In light of the emphasis of previous affordance research on the linear dimensions of the animal's body as a frame of reference and in light of the awareness of the fact that one's own spatial dimensions may not lay a basis for all affordances, the present study went beyond the spatial body dimensions into the domain of kinematic relations. As such, it attempted to present the animal's actions (with their spatiotemporal character), rather than the animal's body, as a frame of reference. The central question was whether it is possible to perceive affordances involving kinematic relations without executing the actions relevant for those affordances (as is the case for affordances for which geometric scaling is appropriate).

To this end, our experiments investigated the circumstances under which perceivers can accurately determine whether a ball projected in the sagittal plane is catchable. The catchableness of a fly ball depends both on the trajectory of the ball and on the locomotory and other action capabilities of the would-be catcher. Therefore, the boundary that separates catchable and not catchable is not a fixed distance, but a distance–time combination in which distance grows (at least over some range) as a function of time squared. In other words, that boundary does not depend on the leg length or eye height of the catcher per se but on the running speeds and accelerations he or she can develop. We found that measures that included time (acceleration and velocity) were significantly better than one that did not (distance).

Because the catchableness of balls landing at a distance can be specified by vertical optical acceleration only when the catcher is locomoting, we expected that stationary perceivers would not accurately perceive catchableness. The results of Experiment 1 revealed that stationary perceivers, both expert outfielders and nonexperts, are indeed poor perceivers of catchableness. Thus, there is no reason to assume that observers can use either other optical information or knowledge about the action capabilities stored in memory. The second experiment directly compared judgments of catchableness of stationary and freely moving perceivers. The results show that running actions prior to making perceptual judgments about the catchableness of fly balls improve these judgments significantly. Simply running toward the ball for a limited amount of time reduces the error in judgments by almost one half.

In addition to the availability of information, another factor may have contributed to the better performance in the motion condition of Experiment 2. Heft (1993) argued that experiments in which observers make perceptual judgments often allow for an analytical stance with respect to a perception–action process that is normally unreflective. Making perceptual judgments a subsidiary part of another more inclusive task, he argued, should lead to a better performance. In Heft's study on the perception of reachability, such an improvement indeed occurred.

In our case, the same may have occurred. The stationary situation seems more likely than the motion situation to invite an analytical stance. However, it is probably less likely that this would occur in Experiment 1 given the time pressure to respond as quickly as possible; Heft (1993) also found an improvement of reachability judgments in the time-limited condition. As an aside, it is interesting to note that in Heft's subsidiary task condition, in which participants performed best, participants were moving (they had to swivel around on the chair to face the marker, the reachability of which had to be judged). Although the movements of Heft's participants were not the task movement itself (reaching), contrary to our observers' movements, they may have provided Heft's observers with additional information about reachability (see Bingham & Stassen, 1994, for an account of the importance of head movements for perception of distances).

What remains to be considered is why judgments, despite the improvement compared with the stationary condition, were still about 20% off in our motion condition. A possible explanation is related to the short-distance run. Initiating locomotory movements takes about .50 s (Oudejans, Michaels, & Bakker, in press), leaving about .50 s for running in the motion condition. In this half, a second observers must bring vertical optical acceleration to zero (that is, below the detection threshold) for the ball to be perceived as catchable. For some balls, those that would land close to the observer, this change will be realized easily. For balls landing far away, this would be more difficult. This leaves a range of landing locations in which some change in vertical optical acceleration may occur during the time the glasses are transparent, but that change will not be sufficient to specify unequivocally whether the ball is catchable or not. Thus, although vertical optical acceleration may have changed sufficiently with respect to some balls, the running time (and therefore distance) was not (always) long enough to expect it to happen on all trials. Thus, even in the motion condition, catchableness would not have been specified on every occasion. As to why the observers consistently overestimated catchableness, it may be that the catcher's acceleration itself may have brought optical acceleration below threshold, even though the critical velocity had not yet been achieved (see, in the Appendix, the discussion of the contribution of $\ddot{X}$ to optical acceleration).

The positive influence on perceptual accuracy of a mere half second of action makes clear that information about the environment relative to the observer and his or her actions has to be available for the observer to perceive the affordances of the environment. In the case of catchableness, actions are needed to determine where the boundaries of these actions are, even for expert outfielders. Thus, only when optical acceleration reflects the combined effects of ball trajectory and catcher locomotion can it be information about the ball's catchableness. It is an optical invariant in which observer and environment naturally come together. As such it provides a nice illustration of an information source in the ecological sense that can be used for prospective control of actions (Michaels & Oudejans, 1992).

Up to now, we have been concerned with the boundary between catchable and not catchable, without much attention to the actions that are separated by the boundary. In this context it must be noted that the fact that catchableness is ambiguous when the catcher is standing still is not a problem for the catcher because, initially, he or she need only know the direction in which to accelerate. It is only during the pursuit of the ball that the consequent action categories are of interest, namely, whether to continue as fast as possible or to slow down to catch the ball on the bounce. It would be interesting to investigate how the critical point of catchableness relates to the transition to catching on the bounce in the baseball situation to ensure that the batter gets no more than a single. The difficulty that natural-turf players exhibit when first playing on astroturf—when the ball bounces over their heads—indicates that other factors can determine behavior at the action boundary. In general, the boundaries between action categories are not exclusively determined by the demonstrable body-scaled or action-scaled metric. This is also illustrated by the work of Warren and Whang (1987), who studied the visual guidance of walking through apertures. They determined that the ratio of aperture to shoulder width at which actors start rotating their body to walk through an aperture is 1.3 whereas, in principle, with any ratio greater than 1, body rotation is not needed. Thus, something other than mere shoulder width determines the action.

A variety of permanent or temporary states (e.g., aging, disability, fatigue, anxiety) can also affect action boundaries (e.g., Konczak et al.'s, 1992, demonstration of the effects of joint flexibility on stair climbing). One can imagine, for example, fatigue being an important factor for the catchableness of fly balls, in which the boundary may shift according to the degree of fatigue because of its effect on running speed. Fortunately, when one has an information source that informs about the motion of the ball relative to one's own actions, fatigue (and other state variables, for that matter) will be "automatically" taken into account. "Invisible" variables are made visible; they need not, therefore, be considered as additional factors; they are part and parcel of perceiving the boundaries of action.

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Appendix

Effect of Catcher Acceleration on Optical Acceleration

Optical acceleration is the second derivative of the height of the center of the ball on a vertical image plane at a unit distance from the eye. This optical height is the actual height of the ball divided by its horizontal distance from the catcher. Assuming that air resistance is negligible, optical acceleration is zero when the trajectory of the ball intersects the eye of a stationary catcher. The function and its two derivatives are given in Equations A1–A3, where y is the optical height and $Y(t)$ and $X(t)$ are the height and distance of the ball at time t, respectively; dots indicate a differentiation with respect to time, and g is the acceleration due to gravity.

$$y(t) = \frac{Y(t)}{X(t)} \quad \text{(A1)}$$

$$\dot{y}(t) = \frac{\dot{Y}(t)\cdot X(t) - \dot{X}(t)\cdot Y(t)}{X(t)^2} \quad \text{(A2)}$$

$$\ddot{y}(t) = \frac{[g \cdot X(t) - \ddot{X}(t) \cdot Y(t)] \cdot X(t) - 2 \cdot \dot{X}(t) \cdot [\dot{Y}(t) \cdot X(t) - \dot{X}(t) \cdot Y(t)]}{X(t)^3}. \quad \text{(A3)}$$

When the (constant) horizontal velocity of the ball, $\dot{X}$ is appropriate to cover the distance, X, between the ball and the catcher in the time that the ball is in the air (i.e., the ball lands at the catcher), the vertical velocity of the ball on the image plane is constant; Equation A2 reduces to the following:

$$\dot{y} = \frac{-g}{2 \cdot \dot{X}}. \quad \text{(A4)}$$

The optics of the situation generalize to that of a moving catcher: $\dot{X}$ becomes the relative velocity of the ball taken with respect to the catcher. This generalization lays the basis for the Chapman strategy—that observers should run in such a way as to zero out optical acceleration, as described also in the text of this article. Unfortunately, there is an error in this formulation. Whereas the $\ddot{X}$ term drops out of Equation A3 when the observer is stationary or running at constant velocity, it must be taken into account in the case of an accelerating or decelerating catcher (or ball, for that matter). This was not done by Chapman (1968), nor by those who subsequently explored optical acceleration as a basis for locomotion in catching (Babler & Dannemiller, 1993; McLeod & Dienes, 1993; Michaels & Oudejans, 1992; Tresilian, 1995).

The effect of including $\ddot{X}$ is not trivial. As can be seen in Equation A3, its inclusion contributes a value equal to the catcher's acceleration times Y/X^2 to the optical acceleration. Given that a catcher might accelerate on the order of 2 m/s^2 to catch a ball, say, at a height of 2 m and at a distance of 10 m away, the resulting addition to optical acceleration would be .04. To illustrate the consequence of this contribution, Figure A1 presents the first 1.5 s of optical acceleration (both with and without the $\ddot{X}$ term included) of a ball with flight characteristics roughly equal to those

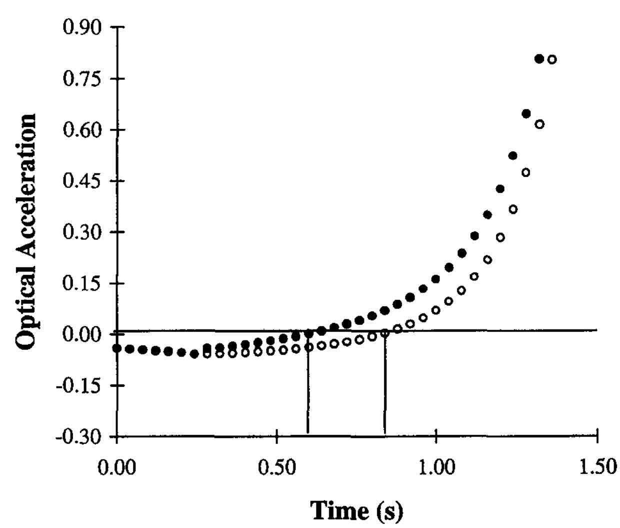

Figure A1. Vertical optical acceleration as a function of time with (closed dots) and without (open dots) the $\ddot{X}$ term included (see text for details).

used in the current experiments (a flight time of 2 s, initial distance from the catcher of 20 m, and a ball travel of 18.3 m). The computation assumes that the catcher accelerates at 2 m/s^2 after a reaction time of .25 s and continues to accelerate (so that the catcher actually overruns the ball). The two lines start to split at .25 s when the catcher½pick;permnew;0;1 begins the acceleration. Notice that the optical acceleration line for the solid dots, which include $\ddot{X}$, reaches zero considerably earlier (about .25 s) than the line for the open circles, which reflects only momentary velocity and not acceleration.

The fact that optical acceleration will be zero before the time that the catcher reaches the velocity appropriate for catching need not necessarily create problems for the catcher, given reaction time and the reappearance of optical acceleration when the catcher's acceleration stops; thus, we have not included the contribution of the catcher's acceleration to optical acceleration in the text of our article. Nevertheless, it needs to be taken into account by models of control laws that relate optical acceleration to the variables of action, such as that of Tresilian (1995).

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