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Shedding Some Light on Catching in the Dark: Perceptual Mechanisms for Catching Fly Balls

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To catch a lofted ball, a catcher must pick up information that guides locomotion to where the ball will land. The acceleration of tangent of the elevation angle of the ball (AT) has received empirical support as a possible source of this information. Little, however, has been said about how the information is detected. Do catchers fixate on a stationary point, or do they track the ball with their gaze? Experiment 1 revealed that catchers use eye and head movements to track the ball. This means that if AT is picked up retinally, it must be done by means of background motion. Alternatively, AT could be picked up by extraretinal mechanisms, such as the vestibular and proprioceptive systems. In Experiment 2, catchers reliably ran to intercept luminous fly balls in the dark, that is, in absence of a visual background, under both binocular and monocular viewing conditions. This indicates that the optical information is not detected by a retinal mechanism alone.

Although outfielders continue to catch fly balls without problems, scientists are still in search of the perceptual information that makes this behavior possible. Research has addressed both what information might control hand movements in interception (Lee, 1976; Lee, Young, Reddish, Lough, & Clayton, 1983; Regan, Beverley, & Cynader, 1979; Savelsbergh, Whiting, Burden, & Bartlett, 1992) and what might guide locomotion to the landing location of the ball (Babler & Dannemiller, 1993; Brancazio, 1984, 1985; Dienes & McLeod, 1993; McBeath, Shaffer, & Kaiser, 1995; McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992; Todd, 1981; Tresilian, 1995). Our concern here is with the latter question—how locomotion is controlled. Predictive strategies—perceiving or computing where the ball will land and running to this predicted location—find little experimental support (Saxberg, 1987a, 1987b; Todd, 1981; Tresilian, 1995; see also McBeath et al., 1995). But even when predictive strategies are not considered, at least three

monocular¹ options remain: The acceleration of the tangent of the elevation angle (AT), the acceleration of the elevation angle itself, and the linear optical trajectory.

Acceleration of the Tangent of Elevation Angle

Chapman (1968) noted that when the (near-parabolic) trajectory of a fly ball traveling in the sagittal plane (the most difficult case for the catcher) intersects the eye of the catcher, the projection of the ball on a vertical image plane rises at a constant speed throughout the trajectory. That is, the tangent of α —the angle between the ball, eye, and the horizontal (see Figure 1)—increases linearly throughout the trajectory; thus, its acceleration, $d^2(\tan \alpha)/dt^2$, is zero. Chapman proposed that catchers make use of this to catch fly balls: To get to the right place at the right time, a catcher needs only to keep the acceleration of the tangent of α (AT) near zero,² which ensures that the trajectories of ball and eye will eventually meet. The catcher must continuously detect the sign of AT; positive AT requires that the catcher accelerate

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¹Whereas both monocular and binocular information could guide locomotion in catching, attention has been focused on monocular information. This focus is in part motivated by the success of one-eyed players in a variety of sports. Nevertheless, it is always judicious to compare binocular and monocular viewing when binocular information is available, as in real catching situations, as we do in Experiment 2.

²Several terms have been used for this information source. Although Michaels and Oudejans (1992) used the term *vertical optical acceleration*, followed by McBeath et al. (1995) with *optical acceleration cancellation*, Babler and Dannemiller (1993) used the term *image acceleration*. McLeod and Dienes (1993; Dienes & McLeod, 1993) and Tresilian (1995) preferred *acceleration of tangent of the projectile's elevation angle*, which captures the source in its most general form. Therefore, we adopt this last term in a shortened version—*acceleration of tangent*—abbreviated simply to AT.

Figure 1. Schematic representation of elevation angle of gaze. Y is the height of the ball; D is the horizontal distance between the ball and the observer.

backward (i.e., decrease anterior speed or increase posterior speed), whereas negative AT informs the catcher to accelerate forward (or decrease posterior speed) to make the catch.

Todd (1981) found no support for the use of AT in his computer simulation experiments, but several studies have since found that real locomotion in catching is consistent with the use of AT (McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992). Additional results from Babler and Dannemiller (1993) have shown that the detection threshold for acceleration is sufficiently sensitive (cf. Calderone & Kaiser, 1989; Schmerler, 1976), making the use of AT more plausible. Further, Dienes and McLeod (1993; McLeod & Dienes, 1996) and Tresilian (1995) demonstrated the robustness of AT under various conditions.

Acceleration of Elevation Angle

Brancazio (1985) questioned the utility of AT because it ignores air resistance; the AT of a ball affected by drag is not precisely zero when the ball is on a collision course with the eye. He suggested that the acceleration of angle itself is better, at least for initiation of locomotion in the proper direction, because it works for ball flights undergoing drag.

Brancazio's alternative is not without problems. First, it introduces a two-component strategy, one component for movement initiation and another for the control of running speed (bringing the velocity component of the ball perpendicular to the line connecting ball and eye to zero; Brancazio, 1985). Second, as shown by Dienes and McLeod (1993), the acceleration of angle works only when the angle of projection of the ball is not too steep. With steep projection angles (Dienes & McLeod, 1993, used 70° as an example), the informational value breaks down, and the sign of the angular acceleration can no longer be used to initiate action. In addition, Dienes and McLeod (1993) showed that cancellation of AT works even with air resistance; continuous coupling between AT and action ensures that errors due to drag effects will be corrected.

Linear Optical Trajectory

McBeath et al. (1995) were not convinced by the circumstantial evidence surrounding AT and have proposed another information source for the guidance of locomotion in

catching fly balls: linear optical trajectory (LOT). Unlike AT, LOT was derived from and pertains to balls outside the sagittal plane, that is, balls landing to the catcher's left or right. Balls in the sagittal plane are considered a special case, "an aligned 'accidental view'" (McBeath et al., 1995, p. 570). The LOT strategy is to run in such a way that the curvature of the optical path is nulled—that is, to run so as to keep the optical path, a projection on a two-dimensional image plane, linear. This can be done by making the tangents of the lateral and the vertical angles grow proportionally.

Dannemiller, Babler, and Babler (1996) questioned some of the claims of McBeath et al. (1995) and showed that the LOT model works only when AT is also cancelled. Therefore, the LOT model can be considered an addition to AT, instead of an alternative to it, because together they cover all possible fly-ball trajectories—those traveling in the sagittal plane and those traveling outside it. Considered as such, the LOT model is not inconsistent with the use of AT.

All in all, then, AT seems the best bet for the guidance of locomotion in catching fly balls, and therefore we take the use of AT as our working hypothesis. Although we assume (for now) that AT guides locomotion in catching, our investigation of detection mechanisms has implications for any theory of the optical regulation of locomotion in catching.

Detecting AT

A first step in establishing how AT is detected is to examine patterns of eye and head movements in catchers. Previous research on one-handed catching by stationary catchers has investigated two alternatives: detection with a stationary eye (the so-called image-retina system) and detection involving eye and head movements (the eye-head system; Montagne, Laurent, & Ripoll, 1993; Sharp & Whiting, 1975).

Although it is well-known that moving objects are followed with the gaze (Kowler, 1990; Sharp & Whiting, 1975), it has never been established what kind of looking behavior fielders display when they are confronted with a fly ball. In the literature on fly-ball catching, it is generally assumed that fielders indeed follow the ball with their gaze (e.g., Brancazio, 1985; McLeod & Dienes, 1993). But whether and how exactly fixation on the ball is accomplished is unclear. Therefore, the goal of our first experiment was to examine where and how catchers look when they are confronted with fly balls. Because, strictly speaking, fixation on a stationary point is a possibility, our first question was whether catchers fixate on the point of release (or on another stationary point) or whether they indeed follow the ball with their gaze. If they do follow the ball, how quickly after ball release do they start tracking the ball and, once tracking, how long and how well do they keep their gaze on the ball? And what are the relative contributions of eye and head movements?

Whether catchers fixate the background or track the ball has important implications about the kind of mechanism that detects AT (or other information). One can discern four possible detection mechanisms. First, motion of the ball

Figure 2. Schematic representation of the Applied Science Laboratories 4000SU head-mounted eye-tracking system.

across the retina³ might be visually detected. This alternative requires fixation of gaze on a stationary point in the environment so that the ball does in fact move across the retina. Second, if there is pursuit tracking, then the ball is relatively stationary on the retina, and the background moves. In that case, motion detectors would have to respond to motion of the background across the retina; this requires the presence of a visible background. Third, and also assuming the ball is tracked, other perceptual systems, such as the vestibular system and proprioceptive systems, could be responsible for detecting the eye and head movements created by tracking. If this were the case, a visible background would not be necessary. Finally, detection could be accomplished by a combination of retinal and extraretinal mechanisms, as would be necessary if tracking were sporadic or inaccurate. The ball motion across the retina would be picked up by retinal mechanisms, and the eye and head movements would be picked up by vestibular and proprioceptive mechanisms.

Thus, the aim of Experiment 1 was to determine whether balls are continuously tracked. If there is no tracking, detection of ball motion across the retina is implicated. If tracking is sporadic or noisy, only the fourth possibility is viable (a combination of retinal and extraretinal mechanisms). If tracking is good, then the second (background motion across the retina) and third (extraretinal motion detection) possibilities remain. Finally, to discriminate among possible extraretinal mechanisms, it is important to ask whether tracking, if it occurs, uses eye movements, head movements, or both.

Experiment 1

Method

Participants. Thirteen males with general experience in ball sports (such as soccer, tennis, cricket, and basketball) participated in the experiment. Their average age was 24 years (range = 19–29). All reported normal or corrected-to-normal vision.

Apparatus. We used an eye-movement registration system (ASL 4000SU, Applied Science Laboratories, Waltham, MA; see

Figure 2) to register eye and head movements and to find out where the observers were looking with respect to projected balls. The system consists of a lightweight eye camera mounted on a headband, an adjustable visor assembly, a scene camera, also mounted on the headband, and a control unit. A computer and two monitors (one to display the scene, including the point of gaze, and one to display the eye and pupil) were connected to the control unit. The system was set up and calibrated so that the scene monitor displayed the observer's central field of view and a cursor indicating the point of gaze within the field (see Figure 2). The scene, including the point-of-gaze cursor, was videotaped at 50 Hz with an S-VHS Panasonic video recorder.

Design. Six blocks of 10 balls were hand thrown toward the standing observer. On two thirds of the blocks, the observer remained stationary and was instructed to act as naturally as possible with respect to his looking behavior when confronted with the balls. The balls landed either behind or in front of him, at a near or a far location. In the remaining blocks the observer was instructed to try to catch the balls by taking one or two steps forward or backward.⁴ These balls were all projected close to the observer.

To determine whether looking behavior depended on seeing the thrower, we also repeated the experiment with a ball-projection machine for 2 of the 13 participants.

Procedure. Because of the light sensitivity of the eye camera and the scene camera, the recordings were made in a dimly lit gymnasium (5.5-m high). The balls were thrown in the sagittal plane of the observers, as high as the ceiling allowed. Balls landing in front of the observer were projected from an initial distance of 16 m; near balls landed 0–7 m in front of the observer, and far balls, 7–11 m. Balls landing behind the observer were thrown from an initial distance of 9 m; the range of balls landing near to the observer was 0–4 m; far balls landed 4–9 m behind the observer. Flight times were approximately 1.8 s.

After the observer was instructed and the headband was donned, the system was calibrated. Following the calibration procedure of 5–10 min, the recording started. The order of the behind and in-front conditions was reversed with every new participant. Within

³We mean, of course, motion of the image of the ball; for simplicity we use the *ball* on the retina.

⁴Because of the delicate equipment, the catchers were instructed to take no more than a few steps toward the landing location of the ball and to do so gingerly.

these conditions the order of the far and near blocks also alternated, always followed by the catching block. The calibration was checked every 10 trials and recalibrated if necessary.

Data reduction. The videotapes were copied, and a unique time code, called a vertical interval time code, was added with an Alpermann and Velte Time Code 30 generator (Alpermann & Velte Electronic Engineering, Wuppertal, Germany). We used a video frame grabber and a digitizing program to determine the release time of the ball, the moment the eyes started to move (indicated by motion of the gaze cursor), the moment the head started to move (indicated by motion of the scene camera), and, when visible, the end of the ball trajectory. For some conditions of some participants, the point-of-gaze signal was not sufficient to permit analysis, so the eye- and head-movement latencies presented below were from 10 and 8 observers, respectively.

In addition to these analyses of the scene recordings, individual representative trials (one per condition) were fully analyzed: The positions of the ball, the gaze cursor, and a stationary point in the environment were digitized for as long as the ball was in view. Angles from the horizontal of ball, gaze, eye, and head were computed on the basis of the known height and initial distance of the thrower. These analyses were done for 11 participants (i.e., all participants except the 2 who also received machine-projected balls). Because in three conditions the quality of the recordings did not allow digitizing of any of the trials, 63 trials were fully analyzed.

Results

Preliminary inspection of the video recordings revealed that observers used eye and head movements to follow each ball with their gaze. In general, after eye-movement initiation, observers pursued the ball smoothly (the gaze cursor stayed on or close to the ball) as long as could reasonably be expected given the trajectory. In the front conditions, balls were followed on average for 95% of the entire trajectory ($SD = 5\%$).⁵ In the behind conditions, tracking stopped because the balls disappeared from view over the observer's head. Close tracking occurred with both hand-thrown balls and machine-projected balls. Only occasionally did a fixation followed by a saccade occur after the observer had started to follow the ball with his gaze. An analysis of the precision of tracking and of the relative contributions of eye and head movements is presented below. First, we briefly consider the latencies of the eye and head movements.

Latencies of eye and head movements. Table 1 shows how quickly after ball release the line of gaze jumped to the ball in the different conditions. The average intervals between the jump of gaze and the onset of head movements are also presented in Table 1. (One observer displayed no head movements in the hand-thrown front-far and behind-near conditions.) For the hand-thrown balls, fixation jumped to the ball within 100 ms, followed by head movements within the first 200 ms after ball release. With machine-thrown balls (2 participants), for which observers could not anticipate the moment of ball release, the eye-movement latency was considerably longer, 200–250 ms, followed quickly by additional head rotation.

A Landing Position (front, back) $\times$ Condition (catch, far, near) repeated measures analysis of variance (ANOVA) on eye-movement latencies for the hand-thrown balls revealed

Table 1

Means and Standard Deviations of Eye and Head Rotation Latencies (in Milliseconds) in the Different Conditions in Experiment 1

Condition	Hand-thrown ball				Machine-projected ball			
	Eye		Head		Eye		Head	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Back-far	69	36	21	43	243	3	55	15
Back-near	74	25	29	54	216	2	70	56
Back-catch	73	27	-3	50	220	32	38	14
Front-far	103	49	76	66	240	20	70	30
Front-near	90	38	61	40	228	4	62	38
Front-catch	86	32	31	60	243	17	26	6
<i>M</i>	83	13	36	28	232	12	54	18

Note. Eye latencies were relative to ball release; head latencies were relative to initiation of eye movements.

only a marginal effect for landing position, $F(1, 9) = 4.76$, $p = .057$. The jump of the point of gaze to the ball tended to occur somewhat later for balls landing in front of the observer (93 ms) than for balls landing behind the observer (72 ms). When one considers that balls landing behind an observer rise optically more quickly than balls landing in front, this finding is not surprising. A similar ANOVA on head-rotation latencies (relative to eye-movement latencies) for hand-thrown balls yielded no significant effects.

To reiterate, watchers and catchers do not continue to fixate the point of release of lofted balls; using both eye and head rotations, their gaze quickly springs to the ball and seems to be maintained there. Although the latencies of eye and head movements depend on how the balls are projected, where they land, and whether they are to be caught, all latencies are consistent with previously reported reaction times for eye movements (see also Shank & Haywood, 1987; Sharp & Whiting, 1975).

Accuracy of tracking. To examine the accuracy of tracking, we computed the average absolute angular difference between the ball angle and the gaze angle for each digitized trial (63 in all; see the *Method* section of this experiment). The most extreme average deviation we found was 2.1° ($SD = 1.10$) over participants in the back-far condition. A Landing Position (front, back) $\times$ Condition (catch, far, near) repeated measures ANOVA on the absolute differences between gaze and ball angle yielded no significant effects. Thus, tracking in the different conditions appears equally accurate.

We also examined individual trials instead of averages over participants. Figure 3 reveals that on 44 (16 + 28) of the 63 digitized trials, tracking stays, on average, within 2° of the ball; on 53 of the 63 trials it stays within 3° . On only 1 of the 63 analyzed trials does the average absolute difference

⁵Near the catch, both the ball and the gaze cursor often disappeared from the scene, as recorded by the scene camera, because of limited viewing angle. It might well have been that tracking continued.

Figure 3. Numbers of trials on which the difference between ball and gaze angles stayed within a certain range in Experiment 1.

between gaze and ball exceed 5° (viz., 5.25°), and as we note shortly, it represents the saccadic behavior of Participant 13, the only participant showing this kind of behavior. Overall, these data provide clear evidence that pursuit tracking of the balls was both accurate and continuous. Once an observer jumped to the ball with his gaze, his gaze stayed on the ball.

Eye and head contributions. We turn attention now to the relative contributions of eye and head movements to tracking the ball. With the exception of the saccade maker, all observers demonstrated continuous tracking. An example of a set of digitizations for a typical individual observer is presented in Figure 4; the figure shows that the ball (filled circles) and gaze (open circles) rose relative to the horizon. In addition, it depicts the magnitude of the two components of gaze: head position (relative to initial head position and shown by filled triangles) and eye position (with reference to

Participant 12

Figure 4. Angles from the horizontal of ball, gaze, eye, and head of Participant 12 for one representative trial per condition in Experiment 1. Front trials are depicted in the left panel, back trials in the right panel. Near trials are shown at the top, far trials in the middle, and catching trials at the bottom.

the head and shown by open triangles). The relative positions of the open and closed triangles, then, illustrate how much eye movements and head movements, respectively, contributed to the gaze angle. We noticed that in the case of this particular observer, all trials showed some contribution of both eyes and head to tracking, though the eyes tended to move considerably more than the head.

We observed considerable differences, however, both between and within observers in the relative contributions. The left panel of Figure 5, for example, shows that during the front-near trial of Participant 5 (top graph), tracking was due almost entirely to head movements; during the front-far trial (middle graph), the tracking primarily constituted eye movements; during catching (bottom graph), eyes and head combined to do the job. Different contributions of eye and head movements can also be seen for the other observers (see, e.g., Figures 4 and 5, right panels).

The upper two graphs in the right panel of Figure 5 illustrate what we identified as saccadic behavior—fast eye movements separated by stationary plateaus.

We computed percentages of gaze movement due to eye movements and the percentages due to head movements. Because these percentages are complementary, only the head-movement percentages are presented in Table 2. The table also includes the standard deviations, which indicate that there are large individual differences. Over all analyzed trials, the contribution of head movements ranged from 0 to 100%. On average the head contribution was somewhat less than the eye-movements contribution. In 45 of the 63 analyzed trials, eye movements contributed a greater proportion to gaze tracking than did head movements; in the remaining 18 trials the reverse was true.

It is interesting to note that in the catching condition, eye and head movements seemed to contribute more evenly than

Figure 5. Angles from the horizontal of ball, gaze, eye, and head of Participants 5 (left panel) and 13 (right panel) for one representative trial per front condition in Experiment 1. Near trials are shown at the top, far trials in the middle, and catching trials at the bottom.

Table 2
Relative Contributions of Head Movements to Gaze Movements (as Percentages) Averaged Over Participants per Condition, and Their Standard Deviations, in Experiment 1

Percentage	Front			Back		
	Near	Far	Catch	Near	Far	Catch
<i>M</i>	39.6	24.6	43.0	28.5	39.8	47.5
<i>SD</i>	33.4	27.3	20.2	29.4	36.1	18.7

in the watching conditions (see, e.g., the left panel of Figure 5). To find out whether this difference in contribution between the catching and the watching conditions was significant, we computed the absolute differences between the head percentages and 50%. A Landing Position (front, back) $\times$ Condition (catch, far, near) repeated measures ANOVA on these percentages yielded a significant effect on condition, $F(2, 16) = 9.94, p < .005$. A Newman-Keuls post hoc analysis revealed that the contribution of head movement was closer to 50% in the catching conditions (mean deviation from 50% = 17.7) than in the watching conditions ($M_s = 30.7$ and 34.1 for the far and near conditions, respectively, $p < .01$). This indicates that catching leads to a more even combination of eye and head movements rather than only watching, when one or the other tends to dominate.

We conclude with two final observations. First, the saccadic behavior of Participant 13 was seen in the perceptual conditions only; the saccades disappeared when he tried to catch the balls (see Figure 5, right panel, bottom graph). The same is true for the behind conditions of Participant 13 that are not shown here.

Second, the results revealed that tracking behavior does not depend on the speed of projection (at least, not within the speed ranges that were used). The speed of the balls was different in the different conditions. For example, the behind-far balls were thrown much faster than the front-far balls, yet tracking accuracy did not differ significantly among conditions despite differences in speed.

Discussion

When confronted with fly balls traveling in the sagittal plane, catchers' eyes spring to and then smoothly track the ball with their gaze shortly after the ball is launched. Tracking is continuous and accurate to within a few degrees. Tracking is accomplished by a flexible system involving eye and head movements, whereby the contribution of each of these kinds of movements can differ both within and between observers.

The results also clearly suggest that the information for catching fly balls is not picked up via motion of the image of the ball on the retina. The information source used to guide locomotion in catching must be picked up some other way. Because tracking, once started, was continuous, another in our list of possible mechanisms must also be excluded—a combination of extraretinal and retinal information. Two possibilities remain. The *retinal* solution of information

pickup that remains is the pickup of retinal motion of the background. The *extraretinal* solutions, involving vestibular information and/or proprioceptive information from eye and neck muscles, are also not excluded. In Experiment 2 we turn our attention to discriminating between the retinal and the extraretinal alternatives.

Experiment 2

If detection of motion of the background across the retina provides the perceptual basis for locomotion in catching, then running to catch should not be possible if there is no background. One way to remove background motion in a fly-ball situation is to project luminous balls in the dark. We already know that simple one-handed catching by stationary participants is possible in the dark (von Hofsten, Rosengren, Pick, & Neely, 1992; Rosengren, Pick, & von Hofsten, 1988; Savelsbergh & Whiting, 1988, 1992), although performance was poorer than in a normally illuminated environment. But what happens when locomotion is required for catching in the dark?

If running to catch is possible in the dark, then extraretinal mechanisms would seem implicated. If running to catch cannot be done in the dark (and running per se is not the problem), then apparently a visually textured background is needed. It is difficult to make a prediction about what will happen in the dark on the basis of baseball practice. On the one hand, there is the "high sky phenomenon"; some players report more difficulty catching high fly balls against a clear blue sky or during night games, situations in which there is little or no optical texture (Miller, 1979). On the other hand, outfielders are regularly successful at catching such balls, so catching a ball that traverses an untextured background is possible. However, in a baseball game, one cannot discard with certainty the possibility that background motion is registered by peripheral vision. Part of the environment is, of course, always visible in the periphery.

To find out whether the pickup of AT requires the presence of a visual background, that is, to distinguish between the retinal and extraretinal alternatives, we asked participants to catch luminous fly balls in an otherwise completely dark environment (thus, an environment without even a peripheral visual background). Failure to locomote appropriately is ambiguous; it could be due either to problems with running in the dark or with perceiving ball trajectory, or both. To determine whether any observed deterioration of catching performance is due to observers' failure to accurately perceive ball trajectory, we also had two judgment conditions (dark and light), in which observers had to determine as quickly as possible whether a ball would land behind or in front of them.

Success in catching in a pitch-black environment, in contrast, would implicate an extraretinal pickup of information. To ensure that any success that catchers may have in catching in the dark is not due to possible binocular sources (see Footnote 1), we examined catching and judging in the dark both monocularly and binocularly in this experiment. Success in catching under monocular conditions in a pitch-

dark environment would support the extraretinal pickup of information.⁶

Method

Participants. Twelve males participated in the experiment. Their average age was 29 years (range = 22–39). None of the observers had experience in competitive baseball, although all of them had experience in other ball sports. All participants reported normal or corrected-to-normal vision. They were divided into two groups: One group did the experiment binocularly, the other monocularly.

Design. The experiment (binocular or monocular) consisted of four conditions: the combinations of two lighting conditions and two tasks (judging landing location and attempting to catch). The gym in which the experiment was executed was either fully lit or pitch black. In the latter condition, luminous balls were used. In the judgment conditions, the task of the stationary observer was to indicate as quickly as possible whether the ball would land in front of him or behind him. He responded by pressing either the button held in the left hand or the button held in the right hand. Which button (left or right) indicated “behind” and which button indicated “in front” was reversed with every new observer. In the catching conditions, the task of the participants was simply to run and catch the balls before the balls hit the ground.

The order of conditions was balanced so that half the participants began with catching and half with judging, half in the dark and half in the light. Furthermore, a catching condition was always followed by a locating condition and vice versa. In each condition, 4 practice trials (or more if requested by a participant in the dark conditions) preceded 20 experimental trials. On half of the experimental trials, the balls landed in front of the initial position of the catcher-observer; in the other half, the balls landed behind the catcher-observer in random order (in both cases balls landed just within catching range for each catcher; see the *Procedure* section of this experiment).

Experimental setup. In a gymnasium (9-m high and 40-m long), tennis balls painted with green phosphorescent paint were machine projected from behind an opaque screen (1.2-m high) toward observers. Balls were shot in the sagittal plane of the observer and had near-parabolic flight trajectories, with the zeniths as high as the gym allowed (8–8.5-m high). The initial distance between the ball-projection machine and the observer was 19 m. In the dark conditions, a full blackout was achieved; the windows were covered with thick black opaque agricultural plastic, as were emergency lights, door edges, and so forth, to make sure that there was no stray light whatsoever. Furthermore, the bright light that was on between trials (see the *Procedure* section) was switched off only just before projection, allowing only a few seconds of dark adaptation. In addition, all participants reported that they could see nothing but the luminous ball during the dark conditions. Finally, in a separate session in the gym, measurements with a Gossen Luna-Pro light meter registered no illumination whatsoever. Five measurements each resulted in a measurement of 0 lx. When a 1,000-W light was on (used between trials; see the *Procedure* section), the light meter measured 0.7 lx at the position of the participant. In full light, the illumination was 175 lx. The luminous balls resulted in an illumination of 0.35 lx at a distance of about 2 cm from the light meter. In the same session, 4 persons (R.O. and 3 naive participants) were asked if they could see how many fingers were held

up in front of their faces or tell if a held-up hand was open or closed at 20, 50, 100, and 200 cm respectively. They could not.

As a ball came out of the barrel of the ball machine, it passed a slotted optical switch (comprising an infrared source and integrated photodetector), which triggered the timer of an M-24 Olivetti computer (286 processor). In the perceptual conditions, the computer stopped the timer when the participant pressed a button. In the catching conditions, release of a foot switch stopped the timer. The participant stood on the foot switch, a strip 1-m long attached to the floor in the transverse plane of the participant, at the initiation of a trial.

Procedure. After the instructions were read and prior to the actual experiment, the participant attempted to catch 20 balls (10 in front and 10 behind) in full lighting. These balls were projected according to a simple staircase method in order to determine, approximately, the maximal distance at which that participant could catch the balls. In the experiment proper, balls were projected, both behind and in front, to a location that was 1–2 m proximal to the maximal distances for that participant. Thus, all balls that were projected during the experimental conditions were, in principle, catchable in a fully lit environment.

In the full-blackout conditions, the trial began with switching off of a 1,000-W lamp, set up near the ball-projection machine and used to charge the luminous balls. A few seconds later, a luminous ball was projected. After the ball was caught or had landed, the light was switched back on again, and the participant returned to his initial position (in the catching condition). In the lighted conditions, all lighting of the gymnasium remained on for the entire condition. In the catching conditions, the catchers were instructed to stand with both feet on the foot switch. As noted, the time that was registered in these conditions was the time between onset of ball flight and release of both feet from the foot switch. Note that these times were not proper movement-initiation times in that both feet had to be off the strip before the timer was stopped.

Because we were interested only in locomotion to the ball and not in the spatial and temporal accuracy of hand and finger movements, interceptions were defined as hand-ball contacts; hence, when the ball was caught and when it was touched by the hand were considered successful interceptions. A miss was registered when the ball was not contacted in flight.

Results and Discussion

The most important result with respect to catching is straightforward: Observers were reliably able to run and

⁶Although it was not possible for us to register eye movements in the dark conditions, it is unlikely that tracking behavior was different in the dark. With only the moving ball visible, eye movements, with or without corrective saccades, seem obligatory in the dark. Just as one cannot voluntarily make smooth-tracking eye movements in the absence of a moving target, one cannot suppress them completely in the absence of a stationary target (Carpenter, 1988; Kowler, 1990; Murphy, Kowler, & Steinman, 1975), especially if a to-be-caught luminous ball is moving through the field of view. Whether tracking behavior is different in the light and dark is not so much dependent on lighting per se (Collewin & Tamminga, 1984) as it is on the velocity of the target. Although the angular velocities of the balls of Experiment 2 were somewhat faster than the ones in Experiment 1, they did not reach the upper limits of human smooth pursuit velocity (Collewin, Steinman, & van der Steen, 1985; Meyer, Lasker, & Robinson, 1985).

intercept fly balls in the dark. This does not mean that illumination did not affect performance, but, in general, participants were remarkably good. The percentages of interceptions in the catching condition and the percentages of correct responses in the landing location condition for both illumination conditions are presented in Table 3. As shown in Table 3, more balls were intercepted with full lighting (88%) than in the dark (63%), $t(11) = 6.27$, $p < .001$. The number of correct responses in the location condition did not differ significantly between dark (96%) and light (97%) conditions, $t(11) = 0.36$, indicating that observers did not have more difficulty in the dark perceiving where the ball was heading (and assuming, of course, that there was no differential speed-accuracy trade-off between the light and the dark conditions).

A Vision (binocular, monocular) $\times$ Task (catching, locating) $\times$ Lighting (dark, light) ANOVA was carried out on the average response latencies, with vision as a between-subjects factor and task and lighting as within-subjects factors. The analysis revealed that catchers responded earlier in the catching condition (482 ms; roughly after the first quarter of the approximately 2-s flight)⁷ than in the location condition (643 ms), $F(1, 10) = 42.43$, $p < .001$. The effect of lighting was also significant; participants responded significantly faster in the light (534 ms) than in the dark (592 ms), $F(1, 10) = 19.89$, $p < .005$. Thus, the equal-judgment-accuracy effect in Table 3 was compromised by a difference in decision latency. Being in the dark did slow the speed with which participants located landing position or initiated their running movements. This may be one reason for the increased number of misses in the dark condition (see Table 3). Looking with one eye or with two eyes did not affect the speed with which participants responded (562 and 564 ms, respectively), $F(1, 10) < 1$. None of the interactions was significant.

To reiterate, in the dark and thus without background motion, catchers were able to run to the landing location of a fly ball and intercept it on most of the trials, though performance was poorer than that under full-lighting conditions. One explanation of the poorer performance in the dark is that catchers began running later. Another possibility is that catchers simply did not run as fast in the dark as they did in the light.

Rather than belaboring the misses, we find the successes much more interesting. Under the reasonable assumption

that observers tracked the ball, the fact that observers were at all able to run to the landing location of a fly ball in the dark precludes the use of exclusively retinally detected information for guidance of locomotion. Neither motion of the image of the ball across the retina (Experiment 1) nor motion of the projection of a visually textured background across the retina (Experiment 2) appears to be necessary for the guidance of running to catch fly balls.

General Discussion

The goal of the present research was to gain insight into how one detects the optical information necessary to guide locomotion in ball catching. We took as our working assumption the thesis, originated by Chapman (1968), that the acceleration of the ball on an image plane, AT, is the operative optical pattern in controlling locomotion in catching. We designed Experiment 1 to establish whether the information is detected with or without image-of-the-ball motion on the retina. Examination of eye and head movements while looking at or catching fly balls showed that catchers do not continue fixation on the point of release (or on any other stationary point in the environment) but follow the ball with their gaze. We concluded that the information source for guidance of locomotion in the direction of the ball is not detected from motion of the ball on the retina.⁸

Detection of retinal motion of the background offered a possible escape for a retinal mechanism but would require a visually textured background, or at least something visible besides the ball. Hence, in the second experiment, we tested whether running to catch was at all possible in the absence of background texture (including all objects). Contrary to the expectations based on the presumed use of optical information available at the retina (but in line with previous research on one-handed sideward catching), Experiment 2 showed that catching a luminous ball in the dark was possible. Moreover, if eye and head movements are the same in the dark as in the light (and one can safely assume this, given that there is no stationary point to fixate and that the optokinetic reflex would mandate pursuit), then one must conclude that the detection of the perceptual information used to guide locomotion in catching is not mediated (solely) by the retina. Instead, extraretinal mechanisms seem to be involved.

Table 3
Percentages of Successful Interceptions in the Catching Conditions and Correct Responses in the Landing Location Conditions for the Two Illumination Levels in Experiment 2

Vision	Catching		Landing location	
	Light	Dark	Light	Dark
Binocular	84	60	100	100
Monocular	92	67	93	92
Total	88	63	97	96

⁷Total flight times could not be determined in the present study. Earlier experiments using similar flight parameters (see Oudejans, Michaels, & Bakker, 1997; Oudejans, Michaels, Bakker, & Dolné, 1996) yielded average flight times of about 2 s.

⁸It has been shown (see Kowler, 1990) that visual tracking often lags behind the target, so that there is always *some* retinal slip. We doubt, though, that this slip alone could provide a retinally based solution to the locomotion problem. Such slippage, because it reflects both ball motion and eye motion, minimally would have to be used in conjunction with extraretinal information.

One could argue that catchers are forced to behave differently in the dark and in the light, either in terms of the exploited information or detection mechanism. However, as mentioned earlier, catching balls appearing against little or no background (a clear blue sky, a homogeneous cloud cover, or a dark sky during night games) occurs often enough to be considered natural.

Thus far we have not been explicit about the possible extraretinal mechanism(s) that might be used to detect ball motion. We now consider some of the possibilities: the vestibular system, the oculomotor proprioceptive system (see, however, Gauthier, Nommay, & Vercher, 1990), and the proprioception from neck muscles (Mergner, Rottler, Kimmig, & Becker, 1992). Could one (sub)system be responsible for the pickup of the relevant information?

Tracking of the ball using both eye and head movements (and perhaps other body segments) maps the optical pattern onto combined rotations of the head and of the eyes relative to the head. Thus, neither the proprioceptive eye-muscle system alone nor the vestibular system alone could pick up both of these rotations; minimally a combined effort of the vestibular system and the proprioceptive systems of eye and neck muscles is required. The contribution of retinal mechanisms per se in the detection system is to ensure tracking of the ball, that is, to preserve optical kinematics in line-of-gaze kinematics.

One advantage of the major involvement of the vestibular system in detecting rotation of the line of gaze is the processing speed of its signals in the central nervous system, which is much higher than the speed with which visual signals are processed (Brancazio, 1984; Guedry, 1974; Kornhuber, 1974). A second advantage concerns one of the criticisms of the use of AT (see McBeath et al., 1995): Humans are claimed to have low visual sensitivity to acceleration. Involvement of the vestibular system means that AT is picked up by a perceptual system better suited for acceleration detection (Cohen, 1974). According to Guedry (1974), the accelerations involved in normal head movements far exceed threshold magnitudes.

Thus, the present results lead to the claim that *optical* information, that is, patterns exhaustively captured by the optic flow field, in this case AT, is ultimately detected by extraretinal mechanisms. In a way, this illustrates Tresilian's (1990) claim that information as such is *amodal*, that is, "independent of the sensory modalities which carry it, cf. Gibson, 1966" (Tresilian, 1990, p. 231). The geometry of the information remains the same (AT) whether it is picked up via retinal motion, extraretinal motion, or a combination of both. As Gibson (1966) observed, the visual system is not just a pair of eyes or retinas; it consists of a pair of mobile eyes in a mobile head on a mobile body.

The possible contribution of extraretinal mechanisms in picking up information in optical flow fields has recently received considerable attention. Using computer simulations of optic flow, Warren and his colleagues (Warren & Hannon, 1988, 1990; Warren, Mestre, Blackwell, & Morris, 1991; Warren, Morris, & Kalish, 1988) found that for accurate heading perception, visual pickup was shown to be sufficient

(Warren & Hannon, 1988, 1990). Using faster simulated and actual eye rotations, Royden, Crowell, and Banks (1994; see also Banks, Ehrlich, Backus, & Crowell, 1996), on the other hand, found clear evidence that extraretinal information about eye movements affects perceived heading; identical retinal patterns led to different perceived directions (and even path types—linear vs. curved) depending on whether the eyes were moving. These experiments did not, however, investigate possible vestibular contributions.

Our results and those just cited together underscore that event information is not detected by isolated traditional modalities. According to Stoffregen and Riccio (1988; Stoffregen, 1990), it is not the information picked up by separate modalities that is informative. Instead, "the pattern of stimulation across systems is informative. . . . Moreover, . . . much information is available solely in patterns of stimulation across perceptual systems (also known as intermodal invariants)" (Stoffregen, 1990, p. 5; see also Gibson, 1966; Riccio & Stoffregen, 1991; Stoffregen & Riccio, 1988, 1990; Tresilian, 1994). If, indeed, AT is the operative variable in running to catch, it is perhaps best conceived as an intermodal invariant that is not picked up with one classic modality but by virtue of the functional interplay among the visual, vestibular, and muscle proprioceptive systems. We conclude that a "smart" perceptual mechanism (Runeson, 1977) to detect AT would, therefore, have to include input from a variety of classically defined perceptual modalities.⁹

It is unlikely that extraretinal contributions to the pickup of optical information is limited to catching fly balls, especially given that those mechanisms are always picking up information, whether about motion or absence of motion. For instance, time-to-contact information is also often mathematically described as related to the motion on the retina. But just as with AT, in principle these geometrical descriptions of time-to-contact information (see, e.g., Bootsma & Oudejans, 1993, for visual information about time to contact between two objects) leave how this information is picked up (with or without eye and head movements) an open question. In most situations in which time to contact is to be perceived (e.g., one-handed sideward catching, maneuvering through traffic), one probably also tracks the object with which one wants to make or avoid contact (see Tresilian, 1990, for a description of intermodal pickup of time-to-contact information). Therefore, we would suppose that the intermodal character of information pickup may be a general principle underlying perception and action.

⁹A smart mechanism for registering the position of an object in space on the basis of oculomotor, vestibular, and proprioceptive inputs has been presented by Guenther, Bullock, Greve, and Grossberg (1994), and work is under way to generalize this model to one that registers velocity of a moving object (D. Bullock, personal communication, January 31, 1997). Although a simple extension of the Guenther et al. model would not suffice for our purposes because the model requires binocular viewing and binocular fixation, the work illustrates the general way in which an appropriate and smart perceptual device might be assembled.

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